Fishery Data Series No. 11-29

# Assessment of Kodiak Salmon Lakes Using an Autonomous Underwater Vehicle, 2009

by

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and

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July 2011

Alaska Department of Fish and Game | Divisions of Sport Fish and Commercial Fisheries

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**Weights and measures (metric)**

| | |
|---|---|
| centimeter | cm |
| deciliter | dL |
| gram | g |
| hectare | ha |
| kilogram | kg |
| kilometer | km |
| liter | L |
| meter | m |
| milliliter | mL |
| millimeter | mm |

**Weights and measures (English)**

| | |
|---|---|
| cubic feet per second | $ft^3/s$ |
| foot | ft |
| gallon | gal |
| inch | in |
| mile | mi |
| nautical mile | nmi |
| ounce | oz |
| pound | lb |
| quart | qt |
| yard | yd |

**Time and temperature**

| | |
|---|---|
| day | d |
| degrees Celsius | °C |
| degrees Fahrenheit | °F |
| degrees kelvin | K |
| hour | h |
| minute | min |
| second | s |

**Physics and chemistry**

| | |
|---|---|
| all atomic symbols | |
| alternating current | AC |
| ampere | A |
| calorie | cal |
| direct current | DC |
| hertz | Hz |
| horsepower | hp |
| hydrogen ion activity (negative log of) | pH |
| parts per million | ppm |
| parts per thousand | ppt, ‰ |
| volts | V |
| watts | W |

**General**

| | |
|---|---|
| Alaska Administrative Code | AAC |
| all commonly accepted abbreviations | e.g., Mr., Mrs., AM, PM, etc. |
| all commonly accepted professional titles | e.g., Dr., Ph.D., R.N., etc. |
| at | @ |
| compass directions: | |
| east | E |
| north | N |
| south | S |
| west | W |
| copyright | © |
| corporate suffixes: | |
| Company | Co. |
| Corporation | Corp. |
| Incorporated | Inc. |
| Limited | Ltd. |
| District of Columbia | D.C. |
| et alii (and others) | et al. |
| et cetera (and so forth) | etc. |
| exempli gratia (for example) | e.g. |
| Federal Information Code | FIC |
| id est (that is) | i.e. |
| latitude or longitude | lat. or long. |
| monetary symbols (U.S.) | $, ¢ |
| months (tables and figures): first three letters | Jan,...,Dec |
| registered trademark | ® |
| trademark | ™ |
| United States (adjective) | U.S. |
| United States of America (noun) | USA |
| U.S.C. | United States Code |
| U.S. state | use two-letter abbreviations (e.g., AK, WA) |

**Mathematics, statistics**

| | |
|---|---|
| *all standard mathematical signs, symbols and abbreviations* | |
| alternate hypothesis | $H_A$ |
| base of natural logarithm | *e* |
| catch per unit effort | CPUE |
| coefficient of variation | CV |
| common test statistics | (F, t, $\chi^2$, etc.) |
| confidence interval | CI |
| correlation coefficient (multiple) | R |
| correlation coefficient (simple) | r |
| covariance | cov |
| degree (angular ) | ° |
| degrees of freedom | df |
| expected value | *E* |
| greater than | > |
| greater than or equal to | ≥ |
| harvest per unit effort | HPUE |
| less than | < |
| less than or equal to | ≤ |
| logarithm (natural) | ln |
| logarithm (base 10) | log |
| logarithm (specify base) | $log_{2,}$ etc. |
| minute (angular) | ' |
| not significant | NS |
| null hypothesis | $H_O$ |
| percent | % |
| probability | P |
| probability of a type I error (rejection of the null hypothesis when true) | α |
| probability of a type II error (acceptance of the null hypothesis when false) | β |
| second (angular) | " |
| standard deviation | SD |
| standard error | SE |
| variance | |
| population | Var |
| sample | var |

*FISHERY DATA SERIES NO. 11-29*

# ASSESSMENT OF KODIAK SALMON LAKES USING AN AUTONOMOUS UNDERWATER VEHICLE, 2009


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# ABSTRACT

This report presents the first results of using an autonomous underwater vehicle (AUV) to collect high-resolution spatial and temporal data on the abiotic and biotic water quality parameters that influence the growth, survival, and sustainability of wild juvenile sockeye salmon in Karluk and Frazer lakes on Kodiak Island, Alaska. Monthly AUV missions were run in Karluk Lake (May through September) and Frazer Lake (June through September) concurrent with traditional means of collecting limnological data. AUV-collected limnological data consisted of pH, chlorophyll, blue green algae, dissolved oxygen, temperature, and turbidity profiles. Depth readings and side-scan imagery were also recorded every second during the AUV missions. Traditionally collected limnological samples consisted of temperature, light penetration, and dissolved oxygen depth profiles, zooplankton, and water samples at depth. Water samples were processed and analyzed in a laboratory for pH, alkalinity, total phosphorous, nitrate + nitrite, ammonia, and chlorophyll-*a* and phaeophytin-*a* concentrations. AUV depth soundings revealed that Karluk Lake was deeper, yet less voluminous than originally mapped. Frazer Lake depth data also showed deeper basins than what was originally plumbed, yet the overall volume was similar to the original estimate. For both lakes, AUV pH measurements were greater than traditionally estimated pH measurements, AUV surface missions in both lakes also indicated concentrated patches of chlorophyll that were not indicated by traditional methods of sampling.

Key words: AUV, Karluk Lake, Frazer Lake, Sockeye salmon, limnology, bathymetry, zooplankton.

# INTRODUCTION

Understanding the interactions of ecological conditions in lake systems and how they vary over time and space is vital for decoding, and eventually modeling and predicting, various types of productivity for a given body of water (Bilby et al. 1996; Kyle 1992; Stockner and MacIsaac 1996). Despite many years of effort and numerous studies, our understanding of the processes governing salmonid productivity and survival in lake systems has been limited. Use of an Autonomous Underwater Vehicle (AUV) enables rapid, high-resolution mapping of environmental parameters important to salmon production and survival and therefore advances the ability to understand the ecological conditions that affect juvenile salmon survival and growth. This report summarizes the findings from the first year of using an AUV to map whole-lake conditions in Karluk and Frazer lakes.

Ancillary data have become increasingly important for managing fisheries because salmonid returns and survival are often affected by density independent factors such as temperature or precipitation. Limnological data have recently been utilized for corroborating escapement goal recommendations and generating preseason forecasts of adult salmon returns (Honnold et al. 2007b, Volk et al. 2009). Limnological data have also been vital for helping to determine potential causes of declines in salmon productivity. Karluk and Frazer lakes, both situated on the southwest side of Kodiak Island (Figure 1), have recently experienced declines in sockeye salmon (*Oncorhynchus nerka*) productivity. Traditional limnological sampling, which has included the collection of temperature, dissolved oxygen, pH, light penetration, nutrient, and zooplankton data, has occurred to varying extents in both lakes since 1985 to help describe bottlenecks in lake productivity and monitor the effects of subsequent remediation or enhancement actions (Honnold et al. 2007a, Koenings and Burkett 1987, White 1991).

Despite spanning 25 years, these data sets are limited in their ability to describe whole-lake conditions because ecological properties observed on a small spatial scale may not be apparent on larger scales and vice versa (Kiffney et al. 2005). This problem exists for Karluk and Frazer lakes because limnological data are generally only collected 4–5 times a year from only two locations in each of these large lakes. Subsequently, the data are extrapolated to represent the conditions and variability of the whole lake. Thus, the spatial resolution (2 stations per lake) may insufficiently reflect parameter gradients over space and time; Karluk Lake has three main basins, yet only one basin has been sampled in recent years. Similarly, Frazer Lake also possesses several deep pockets separated by underwater ridges that may affect nutrient gradients across lake area and depth, and subsequently habitat quality for rearing salmonids.

One simple way to assess whole lake conditions and parameter variability in lakes is by using an AUV to collect limnology data. The YSI Ecomapper[1] AUV, acquired by the Alaska Department of Fish & Game (ADF&G) with Pacific Coast Salmon Recovery Fund monies, is a free-swimming robot with multiple onboard sensors that collect geo-referenced (latitude, longitude, and depth) water temperature, dissolved oxygen, turbidity, pH, chlorophyll, and blue-green algae data (Figure 2). The AUV possesses an on board computer that stores and runs a user-plotted mission. Once deployed, the GPS unit located in the antenna on top of the AUV guides it along the plotted course as long as the unit is not submerged underwater. On diving missions, which can reach depths as great as 61 m (200 feet), the AUV follows a compass heading to the next waypoint. In addition, the AUV possesses a side-scan sonar system capable of generating bottom profile imagery and detecting fish presence in lakes. The sensor array can be programmed to collect data at varying intervals, recording measurements up to every second for up to a four-hour mission. As all data points are geo-referenced by location and depth, physical characteristics can be mapped and compared to side-scan sonar imagery of fish presence to help identify preferred habitats. These data maps ultimately allow for relatively quick, high-resolution visual assessments of habitat quality and variability in an entire lake.

Bathymetric data are equally vital for assessing salmon productivity. Several quantitative models exist that rely on accurate estimates of lake volume or area to calculate optimal levels of escapement for maximizing production (Koenings and Burkett 1987, Koenings and Kyle 1997). With the AUV's capabilities for collecting geo-referenced depth data, it is possible to reassess lake volume and area in Karluk and Frazer lakes, which were originally estimated over 30 years ago. Changes in lake volume could create substantially different estimates of optimal escapement in the euphotic volume or zooplankton biomass models (Koenings and Burkett 1987, Koenings and Kyle 1997) used to assess escapement goals for these systems.

Increasing the spatial and temporal metrics of limnological data in Karluk and Frazer lakes will eventually lead to better modeling of lake or salmon productivity and stock estimation capabilities, which will aid resource managers in establishing harvest strategies that provide for maximum sustained yields of Alaska's salmon stocks. The YSI Ecomapper AUV allows autonomous and rapid mapping of whole-lake conditions, not just the extrapolation of conditions from a few dispersed data points. This report summarizes the first year of water quality mapping capabilities in two lake systems that support extensive sport, commercial, and subsistence salmon fisheries on Kodiak Island.

# METHODS

The sampling schedule for 2009 is outlined in Table 1. Two limnology/zooplankton sampling stations each were set on Frazer and Karluk lakes in May 2009 (Figure 3; Appendices A and B). Water and zooplankton samples and temperature, dissolved oxygen, and light penetration data were gathered at all Frazer Lake stations. Water samples were collected only from the Upper station in Karluk Lake; physical data and zooplankton samples were collected from both stations (Table 1; Figure 3). Each station's location was logged with a global positioning system (GPS)

[1] Product names used in this report are included for scientific completeness, but do not constitute a product endorsement.

and marked with a buoy. Sampling was conducted following protocols established by Thomsen (2008). Because of the size of each lake, multiple missions over multiple days were required to map lake parameters; the timing of AUV missions overlapped with that of traditional limnological sampling.

## TRADITIONAL LIMNOLOGICAL SAMPLING

### Physical Data

Water temperature (°C) and dissolved oxygen (mg/L) levels were measured with a YSI 55 dissolved oxygen and temperature meter. Readings were recorded at half-meter intervals to a depth of 5 m, and then increased to one-meter intervals. Upon reaching a depth of 20 m, the intervals were increased to every five meters up to a depth of 50 m. A mercury thermometer was used to ensure the meter's calibration. Measurements of photosynthetically active wavelengths (kLux) were taken with a photometer. Readings began above the surface, at the surface, and proceeded at half-meter intervals until reaching a depth of 5 m. Readings were recorded at one-meter intervals until the lake bottom or 0 kLux light penetration was reached. The mean euphotic zone depth (EZD) was determined (Koenings et al. 1987) for the lake and incorporated into a model for estimating sockeye salmon fry production (Koenings and Kyle 1997). One-meter temperature and dissolved oxygen measurements were compared to assess the physical conditions in the euphotic zones of the lake. Secchi disc readings were collected from each station to measure water transparency. The depths at which the disc disappears when lowered into the water column and reappeared when raised in the water column were recorded and averaged.

### Water Sampling

Four to eight liters of water were collected from each station with a Van Dorn bottle from the epilimnion (depth of 1 m). Water samples were stored in polyethylene (poly) carboys and refrigerated until initial processing.

One-liter samples were passed through 4.25-cm diameter 0.7-μm Whatman™ GF/F filters under 15 to 20-psi vacuum pressure for particulate N and P analyses. For chlorophyll-*a* analysis, one liter of lake water from each depth sampled was filtered through a 4.25-cm diameter 0.7-μm Whatman™ GF/F filter, adding approximately 5 ml of $MgCO_3$ solution to the last 50 ml of the sample water during the filtration process. Upon completion of filtration, all filters were placed in individual petri dishes, labeled and stored frozen for further processing at the ADF&G Near Island Laboratory in Kodiak.

The water chemistry parameters of pH and alkalinity were assessed with a pH meter. One hundred milliliters of refrigerated lake water were warmed to 25°C and titrated with 0.02-N sulfuric acid following the methods of Thomsen (2008).

All filtered and unfiltered water samples were stored and frozen in clean polytheylene bottles. Water analyses were performed at the ADF&G Near Island laboratory for total phosphorous (TP), total ammonia (TA), total filterable phosphorus (TFP), filterable reactive phosphorous (FRP), nitrate + nitrite, chlorophyll *a*, and phaeophytin *a*. All laboratory analyses adhered to the methods of Koenings et al. (1987) and Thomsen (2008). Nutrient data were analyzed via linear regression and compared to published ratio values.

### Zooplankton

One vertical zooplankton tow was made at each limnology station with a 0.2-m diameter, 153-micron net from one meter above the lake bottom to the surface. Each sample was placed in a 125-ml polyethylene bottle containing 12.5 ml of concentrated formalin to yield a 10% buffered formalin solution. Samples were stored for analysis at the ADF&G Near Island laboratory. Subsamples of zooplankton were keyed to family or genus and counted on a Sedgewick-Rafter counting slide. This process was replicated three times per sample then counts were averaged and extrapolated over the entire sample. For each plankton tow, mean length (±0.01 mm) was measured for each family or genus with a sample size derived from a student's t-test to achieve a confidence level of 95% (Edmundson et al. 1994). Biomass was calculated via species-specific linear regression equations between dry weight and unweighted- and weighted-average length measurements (Koenings et al. 1987). Zooplankton data were compared to physical and nutrient data via linear regression and published values of length and biomass. Zooplankton biomass data were used to estimate escapement levels by indicating a level of juvenile production that a plankton population can maintain as a forage base following the methods of Koenings and Kyle (1997).

## AUV SAMPLING

In 2009, the AUV was deployed on 31 sampling events between May and September in Karluk Lake and on 11 sampling events between June and September in Frazer Lake (Table 1; Figure 3). AUV missions were not run during May in Frazer Lake because of the time constraints created from accommodating AUV training with a factory representative at the end of May and running Karluk Lake missions. All AUV missions were plotted in VectorMap software on geo-referenced images of each lake (example shown in Figure 4) and then loaded onto the AUV's onboard computer via its own wireless network. Missions were plotted to avoid overlap and increase area coverage to maximize data accuracy for bathymetric mapping. Each deployment and retrieval followed the YSI Ecomapper operation manual (YSI 2009). Physical parameters were measured every second along the plotted sampling grid throughout each lake. In addition, bottom profiles and fish presence or absence were obtained with the side-scanning sonar. It should be noted that in assessing fish distribution, speciation was not possible from the side-scan sonar footage. Data were downloaded to a field computer and reviewed following each mission.

## DATA ANALYSIS

All data were edited for erroneous measurements. Traditionally collected limnological data were averaged by month, where applicable, for inseason comparisons. Physical data were plotted against depth for each month.

AUV data for both lakes were divided into three regions (an upper, middle, and lower group) as a cursory step to address homogeneity of lake conditions (Figure 3). Average values for each region were compared within and between months. Maps to display spatial and temporal variability of all AUV data in both lakes were created using the Surfer 9 software package. Bathymetric maps were generated from the depth and coordinate data, also using the Surfer 9 program; lake statistics such as area, volume, and mean and maximum depth were also estimated from the bathymetric data. Side-scanned sonar images were reviewed and fish locations were recorded and plotted on lake maps for each month. Fish locations were also overlain on maps of AUV collected physical and nutrient data.

While it is known that nutrients and production are unevenly distributed in lakes, present estimates in each lake are limited by assuming a uniform distribution of these parameters. Traditionally collected limnological and AUV data were compared where possible either graphically or statistically. Averaged AUV data collected from within a one kilometer radius of the established sampling station were compared graphically by depth and month to traditionally collected limnological data from each station (Figure 3). Similarly, AUV data from upper, middle, or lower regions were compared graphically to traditionally collected data (Figure 3).

Estimates of percent difference of lake volume and area were compared between the two methods of data collection. AUV bathymetric data were also employed in an euphotic volume model (Koenings and Burkett 1994) to estimate rearing capacity and optimal escapement for sockeye salmon.

# RESULTS

## TRADITIONAL LIMNOLOGICAL SAMPLING

### Physical Data

#### *Karluk Lake*

The 1-m temperatures in Karluk Lake ranged from 4.0°C in May to 15.3°C in July, averaging 10.4°C over the summer sampling season (Table 2; Figure 5). Dissolved oxygen readings taken at a depth of 1 m were the lowest in August (10.0 mg/L) and the greatest in May (13.3 mg/L), averaging 11.3 mg/L over the sampling season. Input of light penetration data into a euphotic zone depth (EZD) model estimated the EZD at its deepest in August (29.0 m) and it's shallowest in June (18.4 m). The seasonal average of the EZD was 25.0 m (Table 2; Figure 6). Similarly Secchi disc readings were also deepest in August (9.6 m) and shallowest in June (4.5 m).

#### *Frazer Lake*

The 1-m temperatures in Frazer Lake ranged from 3.4°C in May to 14.7°C in July, averaging 10.0°C over the summer sampling season (Table 2; Figure 7). Dissolved oxygen readings taken at a depth of 1 m were the lowest in July (10.0 mg/L) and the greatest in June (14.8 mg/L), averaging 11.8 mg/L over the sampling season. Input of light penetration data into a euphotic zone depth (EZD) model estimated the EZD at its deepest in September (21.1 m) and shallowest in August (15.9 m). The seasonal average of the EZD was 17.4 m (Table 2; Figure 8). Similarly, Secchi disc readings were also deepest in May (7.8 m) and shallowest in July (5.4 m).

### Water Sampling

#### *Karluk Lake*

Water chemistry measurements were fairly stable in Karluk Lake during 2009: pH ranged from 6.65 in May to 7.56 in September for a seasonal average of 7.18 (Table 3). Alkalinity averaged 22.5 mg/L $CaCO_3$, ranging from 21.5 mg/L $CaCO_3$ in July to 23.8 mg/L $CaCO_3$ in June (Table 3). Total phosphorous averaged 5.5 mg/L P, TFP averaged 1.4 μg/L P, and FRP averaged 2.3 μg/L P in Karluk Lake in 2009 (Table 3). Ammonia averaged approximately 4.4 μg/L N. Nitrate + nitrite had a mean of 16.2 μg/L N that decreased from 73.8 μg/L N in May to concentrations below 2.1 μg/L N from June through September (Table 3). Of the photosynthetic pigments, chlorophyll *a* averaged 0.9 μg/L and phaeophytin *a* had a seasonal mean of 0.4 μg/L (Table 3).

### *Frazer Lake*

The pH in Frazer Lake averaged 7.02, ranging from 6.82 in May to 7.42 in September and alkalinity averaged 14.3 mg/L $CaCO_3$, ranging from 13.5 mg/L $CaCO_3$ between June and July and 15.3 mg/L $CaCO_3$ in May (Table 3). Total phosphorous averaged 5.0 mg/L P, TFP averaged 1.4 μg/L P, and FRP averaged 2.1 μg/L P in Frazer Lake in 2009 (Table 3). Ammonia averaged approximately 5.4 μg/L N. Nitrate + nitrite had a mean of 29.2 μg/L N that decreased from 58.3 μg/L N in May to 11.8μg/L N in August (Table 3). Of the photosynthetic pigments, chlorophyll *a* averaged 0.9 μg/L and phaeophytin *a* had a seasonal mean of 0.5 μg/L (Table 3).

## Zooplankton

### *Karluk Lake*

The 2009 seasonal average abundance of Karluk Lake zooplankton was predominately composed of the copepod *Cyclops* (401,858/$m^2$), followed by the cladoceran *Daphnia* (43,564/$m^2$; Table 4). The abundance of *Cyclops* fluctuated over the sampling season, however *Daphnia*, *Diaptomus*, a copepod, and *Bosmina*, also a cladoceran, generally increased in abundance each month (Table 4). Juvenile copepods (nauplii) and immature cladocerans were abundant. Egg-bearing zooplankton were predominantly *Daphnia* (seasonal average 14,252/$m^2$), which increased in abundance from May to August, and *Cyclops* (seasonal average 12,951/$m^2$), which peaked in July (Table 4).

The seasonal weighted-average biomass of Karluk Lake zooplankton was 1,283 mg/$m^2$ for 2009 ranging from 1,020 mg/$m^2$ in September to 1,478 mg/$m^2$ in July (Table 5; Figure 9). Excluding ovigerous individuals, zooplankton biomass was greatest for *Cyclops*, peaking in May (1,142 mg/$m^2$) and declining to 482 mg/$m^2$ in September (Table 5). Seasonal weighted-average biomasses for non-egg bearing *Bosmina* and *Daphnia* were generally low, ranging from less than 10 mg/$m^2$ May to greater than 90 mg/$m^2$ in September (Table 5). Ovigerous *Daphnia* (89 mg/$m^2$) and *Cyclops* (266 mg/$m^2$) both peaked in biomass during July (Table 5).

Ovigerous *Cyclops* (seasonal weighted average of 1.21 mm) were the longest zooplankton collected from Karluk Lake in 2009 (Table 6). *Diaptomus* and ovigerous *Daphnia* were also relatively large with seasonal weighted-average lengths of 0.87 and 0.81 mm, respectively. The smallest zooplankton were *Bosmina*, which had a seasonal weighted-average length of 0.41 mm (Table 6).

### *Frazer Lake*

The seasonal average abundance of zooplankton was 156,245/$m^2$ for Frazer Lake in 2009 (Table 7). Of identifiable zooplankton, *Cyclops*, *Bosmina*, and *Daphnia* were the most abundant taxa. Immature copepods and cladocerans were also abundant during the sampling season (Table 7). *Cyclops* were most abundant in July (112,527/$m^2$) while *Daphnia* were most abundant in September (91,143/$m^2$; Table 7). Similarly, *Cyclops* and *Daphnia* were the most abundant egg-bearing zooplankton; ovigerous *Cyclops* peaked at 12,739/$m^2$ in July and *Daphnia* peaked at 20,648/$m^2$ in August.

The seasonal average biomass of copepods was greater than that of cladocerans in 2009 for Frazer Lake. *Cyclops* biomass ranged from 72 mg/$m^2$ in May to 12 mg/$m^2$ in September, peaking in July at 424 mg/$m^2$ (Table 8; Figure 10). *Bosmina* and *Daphnia* biomasses each increased from less than 7 mg/$m^2$ in May to their peaks in September, each greater than 80 mg/$m^2$ (Table 8).

Ovigerous *Cyclops* had the greatest average length of 1.20 mm, ranging from 1.19 to 1.33 mm (Table 9). The copepods *Diaptomus* (0.91mm) and *Epischura* (0.77 mm) were also among the longest zooplankton sampled. Ovigerous *Daphnia* (0.70 mm) were the longest cladocerans while *Bosmina* were the smallest zooplankton measured, ranging from 0.33 mm in June and July to 0.39 mm in May (Table 9).

## AUV SAMPLING

### Physical Data

#### *Karluk Lake*

Surface temperature, dissolved oxygen, and turbidity were mapped for each month and region relative to location with the exception of the Upper region during September (Appendix A). Lower Karluk Lake was generally colder than the Upper and Middle regions (Table 10; Figure 11). Surface dissolved oxygen concentrations varied minimally from region to region and were similar from May through June, declining in July and then stabilizing during August and September (Table 10; Figure 12). Surface turbidity was greatest during July in the Lower region. Surface turbidity measurements, on average, increased heading south from the Upper to the Lower region of the lake (Table 10; Figure 13).

July and August data best described physical data depth profiles because missions were consistently run at depth. Temperature depth profiles indicated that Karluk Lake stratified by August with the hypolimnion being deepest (~17 m) in the Lower region of the lake (Figure 11). Dissolved oxygen concentrations varied minimally over depth (Figure 12). Turbidity in Karluk Lake appeared fairly homogenous over depth and time with the exception of July values ranging 0.3 to 2.2 NTU in the Middle region and 0.9 to 2.1 for the Upper region (Figure 13).

#### *Frazer Lake*

Surface temperature, dissolved oxygen, and turbidity were mapped from June through September in Frazer Lake (Appendix B). Lower Frazer Lake was generally colder than the Upper and Middle regions each month, with the exception of September when the Upper region was the coldest (Table 11; Figure 14). Surface dissolved oxygen concentrations varied minimally from region to region and were similar from June through September, declining from June to July and then stabilizing during August and September (Table 11; Figure 15). Surface turbidity was greatest during September in the Lower region. Surface turbidity measurements had the greatest variability over lake area from July through September (Table 11; Figure 16).

Depth profiles of averaged physical data were best represented by June and August missions, which were consistently run at depth. July missions were limited to surface data collection because of navigational problems. Temperature depth profiles indicated that Frazer Lake was mixed in June with cooler temperatures in the Lower region of the lake (Figure 14). Dissolved oxygen concentrations varied minimally over depth (Figure 15). Average turbidity measurements in Frazer Lake were fairly homogenous over depth and time, however a maximum measurement of 1,052 NTUs was recorded in August in the Lower region and values in excess of 300 NTUs were recorded in the Upper region during July and September.

## Water Sampling

### *Karluk Lake*

Surface chlorophyll concentrations were generally greatest in June, with the exception of the August measurement from the Upper region, which was the highest average surface concentration for all months and all regions (Table 12). September had the lowest chlorophyll concentrations of the sampling season, with the exception of the July measurement for the Upper region. The Middle and Lower regions had greater surface chlorophyll concentrations than the Upper region from May through July. Maximum concentrations of chlorophyll reached 44.90 μg/L in the Upper region, 271.10 μg/L in the Middle region, and 189.00 μg/L in the Lower region during July sampling. Chlorophyll depth profiles showed variability over location, depth, and time, but were generally low on average (Figure 17). Higher concentrations were measured closer to the surface in all months except May when concentrations increased with depth.

The average surface pH measurements increased from May to their highest levels in June and declined from June to September (Table 12). No one region consistently maintained the highest or lowest pH measurements. Average pH values were similar over depth for each month with the exception of August (Figure 18). During this time, the Lower region had greater pH values than the other regions down to a depth of roughly 15 m, after which pH values appeared to stratify and were similar.

### *Frazer Lake*

Average surface chlorophyll concentrations in Frazer Lake were low (<4 μg/L) during the 2009 sampling season. The greatest concentrations were measured in June and August (Table 13). The Middle region had the highest average surface concentration (3.38 μg/L), which was measured in August. The variability around the surface chlorophyll measurements was the greatest in August as well, as evidenced by relatively large standard deviations and maximum concentrations of 166.70 μg/L for the Upper region, 212.40 μg/L for the Middle region, and 193.00 μg/L for the Lower region. Surface pH measurements in Frazer Lake were highest in July (Table 13). Depth profiles of chlorophyll concentrations showed variability in measurements taken from the Upper and Middle regions in August (Figure 19). June chlorophyll concentrations appeared consistent over location and depth. Chlorophyll concentrations taken in September from the Upper region varied over depth more than the Middle region; measurements from the Lower region were limited to 1.5 m in depth and preclude themselves from an accurate comparison (Figure 19).

The Upper region had a higher pH than the Middle and Lower regions in June, however it was lower in pH than both other regions in August and September. Depth profiles of pH in Frazer Lake showed consistency in June and August, and generally lower in the Upper region of the lake in June (Figure 20).

## Bathymetry

### *Karluk Lake*

The Karluk Lake bathymetric map created with AUV data substantially differed from the original bathymetric map that was created using a fathometer (Table 14; Figure 21). Lake volume estimates differed by 8%. The original estimate of average depth was 21% more than the AUV estimate (Table 14). Visual comparison of the two versions of the Karluk Lake bathymetric map showed differences in the morphology over the lower two-thirds of the lake, as evidenced by the presence of deep pockets in the AUV version and a uniform bottom in the original map (Figure 21).

### *Frazer Lake*

The Frazer AUV bathymetric statistics showed lake area and volume were less than originally estimated. The AUV-generated maximum and average depths for Frazer Lake were greater than originally estimated (Table 14). Review of both maps revealed greater definition in bottom morphology with the newly plotted AUV map (Figure 22). The AUV-based map also included islands that were omitted from the original bathymetric map.

## Sonar Imagery

### *Karluk Lake*

Side-scan sonar imagery indicated fish presence throughout Karluk Lake (Figure 23). Aggregations of fish in the Thumb (eastern arm of lake) and O'Malley (southern arm of lake) basins appeared greater in July and August. June and September imagery showed fish present in the Upper and Middle regions of the lake.

### *Frazer Lake*

June side-scan sonar imagery showed fish presence in only the Lower and Middle regions of the lake (Figure 24). July imagery indicated fish were detected throughout the lake. Fish were detected primarily in the Middle and Upper regions during August and September.

# COMPARISON OF SAMPLING METHODS

### *Karluk Lake*

Comparisons of physical data collected by the AUV within a one-kilometer grid around the traditional sampling station revealed that Karluk Lake temperature, dissolved oxygen, pH, and chlorophyll concentrations substantially varied over depth, space and time when compared to traditionally collected data and to areas not sampled by traditional means (Tables 15 through 18). Specifically, pH and chlorophyll were generally greater when measured by the AUV; temperatures were warmer on average in the spring and fall while dissolved oxygen concentrations showed less variability at surface depths than traditionally collected data (Figures 11 through 13 and 17 and 18). Region-wide comparisons of averaged AUV to traditional data also showed greater variability in data measurements over depth, especially during the spring and fall (Appendices A and B).

### *Frazer Lake*

Comparisons of physical data collected in Frazer Lake by the AUV within a one-kilometer grid around the traditional sampling station revealed that AUV-recorded temperatures were cooler at the southern end (Lower region) of the lake in June and August (Table 19; Figure 14). AUV-recorded dissolved oxygen concentrations were more consistent in general, with greater concentrations in June although June concentrations were substantially less than that collected by traditional means (Table 20; Figure 15). Similar to Karluk Lake, AUV pH and chlorophyll values from Frazer Lake were greater than those estimated by traditional methods (Tables 21 and 22; Figures 17 and 18). Depth profiles showed temperature readings to corroborate one another, however, dissolved oxygen profiles from station 3 at the northern end (Upper region) of the lake varied substantially from the AUV data (Figure 15). June dissolved oxygen depth profiles in particular were substantially greater for both stations compared to AUV dissolved oxygen depth profiles.

# DISCUSSION

Oligotrophic lakes are preferred habitat for rearing sockeye salmon (Carlson 1977; Carlson and Simpson 1996). Limnology data from traditional and AUV collection methods indicated that Karluk and Frazer lakes could be classified as having oligotrophic (low) production levels as defined by several trophic-state indices (Carlson 1977; Forsberg and Ryding 1980, Carlson and Simpson 1996).

Nutrient data may be used to indicate limitations to primary productivity in aquatic environments. A comparison of the photosynthetic pigment, chlorophyll *a,* to its byproduct, phaeophytin *a,* showed that chlorophyll-*a* concentrations were generally proportionally high in Karluk and Frazer lakes (annual seasonal means of 5.0 and 2.2 chlorophyll *a* to 1 phaeophytin *a*, respectively). This signifies that algae levels in both lakes were generally adequate for supporting primary consumption because the potential for algal (phytoplankton) growth existed as chlorophyll *a* was available for photosynthesis (COLAP 2001). Conversely, when primary production is taxed by either overgrazing or poor physical conditions, phaeophytin-*a* levels tend to exceed chlorophyll-*a* levels (COLAP 2001). Historically, only 5% of the phaeophytin-*a* levels have exceeded chlorophyll-*a* levels of Karluk Lake since 1988, yet 19% of the phaeophytin-*a* levels have exceeded chlorophyll-*a* levels of Frazer Lake since 1985. In light of these traditionally collected data, primary nutrients have not appeared to be a limiting factor in Karluk Lake for its level of productivity. For Frazer Lake, the opposite may be true at times, meaning nutrients are not always readily available for photosynthesis.

Traditional and AUV temperature depth profiles for Karluk Lake indicated turnover events occurred in May and September. Frazer Lake turned over in June and September. Karluk Lake was warmer than Frazer Lake through June. Both lakes had similar temperatures from July through September, often exceeding 15°C (considered an optimal temperature for salmonid growth; Brett et al. 1969) within the first 3 meters of the water column. Dissolved oxygen concentrations were at suitable levels for rearing fishes in both lakes, however, there was great variability among the traditionally collected data when compared to the AUV-collected data. This may be in part to the variability that naturally occurs in large systems and the ability of the collection methods to accurately represent lake conditions. It may also be the difference between measurements acquired with different types of probes. Spatial analysis of the AUV temperature data revealed the Lower region of Karluk Lake tended to be cooler than the Middle and Upper regions in the spring and fall. Similar trends were observed in Frazer Lake in June and July. Traditionally collected data often did not reflect these trends which are most likely an artifact of the limited number of samples collected within a given area.

Physical conditions were not limiting to zooplankton. Changes in phytoplankton species composition mediated by physical factors such as water clarity can negatively affect zooplankton consumption and assimilation rates (Wetzel 1983; Kerfoot 1987; Kyle 1996). Cladocerans, which are selective feeders, can have periods of reduced growth or reproduction in the absence of preferred forage (Dodson and Frey 2001). Similarly, Kirk and Gilbert (1990) noted that suspended particles dilute food concentrations in the water column reducing cladoceran population growth rates. For Karluk and Frazer lakes' zooplankton, water clarity normally has not been an issue as evidenced by an average summer euphotic zone depth (EZD) of 17.4 m for Frazer Lake and 24.2

m for Karluk Lake and average summer Secchi disc readings of 6.4 m and 8.8 m, respectively. Turbidity data collected by the AUV further suggested that water clarity in both lakes does not negatively impact zooplankton production; turbidity in both lakes was considered low (< 5 NTUs) by several indices and studies (ADEC 1978, Lloyd 1987, McCabe and Obrien 1983).

It should also be noted that comparisons of Karluk and Frazer lakes' Secchi disc readings to traditionally estimated chlorophyll-*a* concentrations did reveal a weak hyperbolic relationship that is often seen in other lakes (Figure 25; COLAP 2001). Typically, as chlorophyll concentrations increase, Secchi discs become less visible because of increased phytoplankton in the water column and vice versa. The weakness of the chlorophyll-Secchi disc relationships may be in part due to consistently deep EZDs in the lake over time and the inability of traditional water collection methods to represent the variability among limnological parameters over depth. AUV data, which were ground-truthed to the traditional method of chlorophyll estimation, indicated that chlorophyll concentrations varied greatly over lake area and depth. The AUV was able to capture chlorophyll concentrations up to 298 µg/L in Karluk Lake and 212 µg/L in Frazer Lake. This patchiness of chlorophyll measurements suggests that the traditional means of collecting water samples may not accurately represent the dynamic conditions and therefore relationships among variables. The hyperbolic Secchi disc-chlorophyll relationships may also be masked by other particulates, such as sediments in the water column affecting visibility and the lack of contrast in the data to reveal a hyperbolic trend. Because Secchi disc measurements varied greatly respective to chlorophyll-*a* concentrations, perhaps the traditional data lack the necessary contrast to define a hyperbolic relationship. Comparisons of 2009 AUV chlorophyll data to corresponding Secchi disc measurements were limited with only one year of data and inconclusive for both lakes.

Review of the traditionally collected 2009 pH and alkalinity data for both lakes suggested that primary production increased from the spring to the fall. Photosynthesis uses dissolved carbon dioxide ($CO_2$), which acts like carbonic acid ($H_2CO_3$) in water. The removal of carbon dioxide through photosynthesis, in effect, reduces the acidity of the water and therefore pH increases creating a more basic, or alkaline, environment (Wetzel 1983). The monthly average Karluk and Frazer lakes' pH levels increased from May to September during the summer growing season when daylight hours, and therefore photosynthetic rates, were greater. This suggested that sufficient nutrients were available for primary production as evidenced by a noticeable seasonal increase in pH. During July and August, average pH levels decreased, which may be the result of increased zooplankton respiration releasing $CO_2$ into the water. This can be expected because the total zooplankton abundance generally increased over the summer with increased temperatures and forage (phytoplankton) availability and decreased grazing pressure from rearing juvenile salmon that leave the lake during the spring smolt outmigration. Additionally, as zooplankton abundance increases, so does their grazing pressure upon phytoplankton. The cropping of phytoplankton may also reduce the removal of $CO_2$ from the water, and therefore reducing the pH-increasing effect of photosynthesis. Comparisons of AUV data also revealed spatial differences in pH measurements over space and time. The differences were not indicated by traditional sampling methods, which may be expected as only one sample from each lake, each month, was used to profile whole-lake conditions. Alkalinity data indicated that Karluk Lake was fairly resistant to changes in pH and the total phosphorous concentration generally declined after stratifying, which corresponds to how measures of ionic concentration, such as alkalinity, are positively correlated to phosphorous concentrations (Cardoso et al. 2007). This may be explained by the removal of phosphorous from the water column via photosynthesis and sedimentation of those nutrients following a spring turn-over of the lake (Wetzel 1983; Cardoso et al. 2007).

Frazer Lake also showed similar declines in total phosphorous concentrations following stratification, although alkalinity was lower than in Karluk Lake. In comparison to AUV-collected data, pH values from traditionally collected methods were consistently lower for both lakes. This trend maybe the difference between in situ sampling (AUV) compared to the process of collecting, shipping and analyzing a sample in a laboratory environment and the meters used to determine pH. These differences may also be attributed to the variability of conditions within the lake: a small water sample taken from one location may not accurately represent conditions throughout the lake. That the AUV pH data differed among lake regions for given depths supports this as similar pH readings were measured from both the AUV and the laboratory pH meter for the exact same water sample in the lab.

Planktivorous fishes, such as sockeye salmon, can exert top-down pressures on zooplankton communities (Kyle 1996; Stockner and MacIsaac 1996). This type of predation can result in changes to the zooplankton species composition (Helminen and Sarvala 1997; Donald et al. 2001; Thorpe and Covich 2001). Specifically, copepods can enter a state of diapause as an egg or copepdid in response to overcrowding, photoperiod, or predation (Thorpe and Covich 2001). Average monthly biomass estimates for copepods in Karluk Lake increased from May to June, and declined from August to September, which could indicate a response to predation as young-of-the-year fish grow over the summer and become more capable predators. The decline in copepod biomass followed a seasonal high of over 1,200 mg/m$^2$ in July, considered above the satiation level of 1,000 mg/m$^2$ for rearing salmonids (Mazumder and Edmundson 2002), and coincided with temperature and Cladoceran biomass increases in each month. Therefore, it is possible that the high density of copepods coupled with increasing seasonal temperatures caused the copepods to go into a state of diapause in September, essentially removing them from the population and causing the decline in their biomass. The monthly average lengths of *Bosmina* support this hypothesis. Evidence of overgrazed zooplankton populations can be reflected by a reduction in cladoceran body length (Kyle 1992; Schindler 1992). In Karluk Lake, *Bosmina* on average were longer than the minimum elective feeding threshold of 0.40 mm for juvenile sockeye salmon (Kyle 1992) from May through August, but fell slightly below threshold size in September. This suggests that top-down grazing pressures were not severely stressing or substantially removing the larger *Bosmina* from the zooplankton population, and perhaps not as influential upon the zooplankton community as interspecific competition and physical conditions in Karluk Lake prior to September.

In contrast to Karluk Lake, Frazer Lake zooplankton biomasses were near or below starvation levels for juvenile sockeye salmon during May and June. July biomass levels rebounded to roughly 500 mg/m$^2$. Biomass declined in August and remained low through September. The fall zooplankton biomasses, however, do not reflect the increase in cladoceran abundance and their predominance in species composition because of the relatively small sizes of cladoceran taxa. This trend again suggests predation has a negative impact upon the zooplankton population by selectively removing larger individuals from the population.

Side scan sonar data collected from both lakes indicated migratory trends of smolt-sized and adult-sized fish. During June, sonar imagery indicated the presence of small fish in the middle and outlet ends of each lake although July side scan sonar imagery indicated that a small abundance of larger fish were present throughout the lakes. The differences between the June and July imagery may indicate the end of the sockeye salmon smolt outmigration from each lake, and therefore reduced grazing pressure and the subsequent increase in zooplankton biomasses that occurred midsummer. These observations also corroborate historical counts of sockeye smolt outmigration timing. Similarly, larger-sized fish were detected near tributary streams in August and September, which may be adult sockeye salmon returning to their spawning streams. It should be noted that detection of fish location was limited to the path that the AUV scanned. Additionally, although individual fish can be discerned in the imagery, species cannot be identified and enumeration is not possible because any overlap of schooling fish precludes accurate counts and the ability to estimate species composition.

Bathymetric data from the AUV allowed for re-estimation of lake volume and estimates of sockeye salmon productivity. The bathymetric data have not been updated since Karluk and Frazer lakes were initially mapped in the 1960s. The new estimated volume of Karluk Lake was reduced substantially and bathymetry profiles revealed deep pockets in the southern arm of the lake. The assessment of Frazer Lake bathymetry also indicated that the bottom morphology was deeper than originally plumbed and the overall lake volume was less than what was originally indicated. These differences in bottom morphology may affect our understanding of lake turnover events because the deep pockets found in Karluk Lake may serve as nutrient sinks that prevent the redistribution of nutrients trapped in sediments or create anoxic sinks of limited oxygen exchange or turnover. The AUV volume data, when incorporated into an euphotic volume model of lake productivity (Koenings and Burkett 1987), resulted in decreases to recommended escapement goals for both lakes when compared to prior estimates using the original data and same model. For Karluk Lake, this difference was a 31% decrease (from a point estimate of 777,000 to 593,000 fish), and for Frazer Lake, a 6% decrease (from a point estimate of 238,000 to 224,000 fish).

Changes in nutrients and forage bases can significantly impact higher trophic levels such as secondary or tertiary consumers (Kyle et al. 1988; Milovskaya et al. 1998). In some lake systems, these negative changes can cause migratory behavior or decreased juvenile sockeye salmon freshwater survival (Parr 1972; Ruggerone 1994; Bouwens and Finkle 2003). Thus, it is important to know and understand patterns of resource abundance and habitat usage to enhance management of the system and conserve its resources. In light of these data, it is apparent that even from its first year of data collection, the AUV provides a valuable picture of the variability in large lakes. These data have elucidated patterns of ecological processes that suggest the lakes are dynamic and may have areas of preferred habitat for zooplankton or fishes. Continued observation of Karluk and Frazer lakes following these effects may indicate if the rearing environments are at their peak production levels or are limited or overtaxed for current production levels.

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# TABLES AND FIGURES

Table 1.–Sampling dates and methods used for Karluk and Frazer lakes, 2009.

| | Lake | |
|---|---|---|
| Sample dates | Karluk | Frazer |
| 8-May | W, Z | W, Z |
| 29-May | AUV | |
| 30-May | AUV | |
| 31-May | AUV | |
| 20-Jun | | W,Z |
| 21-Jun | | AUV |
| 22-Jun | | AUV |
| 23-Jun | AUV | |
| 24-Jun | W, Z, AUV | |
| 15-Jul | W, Z, AUV | |
| 16-Jul | AUV | |
| 17-Jul | AUV | |
| 19-Jul | | AUV |
| 20-Jul | | W, Z, AUV |
| 18-Aug | | AUV |
| 19-Aug | | W, Z, AUV |
| 20-Aug | AUV | |
| 21-Aug | W, Z, AUV | |
| 15-Sep | | AUV |
| 16-Sep | | W, Z, AUV |
| 17-Sep | W, Z, AUV | |
| 18-Sep | AUV | |

Note: W = water sampling
Z = zooplankton sampling
AUV = AUV sampling.

Table 2.–Monthly and seasonal averages of 1-m temperature and dissolved oxygen, euphotic zone depth (EZD), and Secchi measurements from Karluk and Frazer lakes, 2009.

| | May | June | July | August | September | Seasonal average |
|---|---|---|---|---|---|---|
| Karluk Lake | | | | | | |
| 1-m Temperature (°C) | 4.0 | 9.3 | 15.3 | 13.3 | 10.2 | 10.4 |
| 1-m Dissolved oxygen (mg/L) | 13.3 | 12.3 | 10.1 | 10.0 | 10.9 | 11.3 |
| EZD (m) | 25.3 | 18.4 | 22.8 | 29.0 | 26.9 | 25.0 |
| Secchi depth (m) | 8.8 | 4.5 | 8.4 | 9.6 | 8.3 | 7.9 |
| Frazer Lake | | | | | | |
| 1-m Temperature (°C) | 3.4 | 8.5 | 14.7 | 12.6 | 10.8 | 10.0 |
| 1-m Dissolved oxygen (mg/L) | 13.2 | 14.8 | 10.0 | 10.2 | 10.9 | 11.8 |
| EZD (m) | 16.7 | 16.9 | 16.0 | 15.9 | 21.1 | 17.4 |
| Secchi depth (m) | 7.8 | 6.5 | 5.4 | 7.0 | 6.5 | 6.4 |

Table 3.–Monthly and seasonal averages of water chemistry components, photosynthetic pigment concentrations, and nutrient concentrations from Karluk and Frazer lakes, 2009.

| Sample type | May | June | July | August | September | Seasonal average | SE |
|---|---|---|---|---|---|---|---|
| Karluk Lake | | | | | | | |
| pH | 6.65 | 7.41 | 7.13 | 7.15 | 7.56 | 7.18 | 0.07 |
| Alkalinity (mg/L $CaCO_3$) | 22.3 | 23.8 | 21.5 | 22.5 | 22.5 | 22.5 | 0.16 |
| Total phosphorous (µg/L P) | 5.6 | 6.6 | 4.7 | 5.7 | 4.7 | 5.5 | 0.17 |
| Total filterable phosphorous (µg/L P) | 0.4 | 1.3 | 2.7 | 1.8 | 0.8 | 1.4 | 0.18 |
| Filterable reactive phosphorous (µg/L P) | 2.8 | 2.2 | 1.4 | 3.0 | 2.1 | 2.3 | 0.13 |
| Ammonia (µg/L N) | 3.6 | 3.6 | 4.6 | 6.4 | 3.9 | 4.4 | 0.24 |
| Nitrate + nitrite (µg/L N) | 73.8 | 1.9 | 1.3 | 2.0 | 2.0 | 16.2 | 6.44 |
| Chlorophyll *a* (µg/L) | 1.0 | 1.9 | 0.3 | 0.3 | 1.0 | 0.9 | 0.13 |
| Phaeophytin *a* (µg/L) | 0.4 | 0.3 | 0.4 | 0.4 | 0.6 | 0.4 | 0.02 |
| Frazer Lake | | | | | | | |
| pH | 6.82 | 6.92 | 7.09 | 6.85 | 7.42 | 7.02 | 0.05 |
| Alkalinity (mg/L $CaCO_3$) | 15.3 | 13.5 | 13.5 | 15.0 | 14.0 | 14.3 | 0.17 |
| Total phosphorous (µg/L P) | 4.5 | 5.0 | 5.8 | 5.5 | 3.9 | 5.0 | 0.15 |
| Total filterable phosphorous (µg/L P) | 0.8 | 1.0 | 0.8 | 0.6 | 3.9 | 1.4 | 0.28 |
| Filterable reactive phosphorous (µg/L P) | 2.9 | 1.9 | 1.4 | 2.8 | 1.6 | 2.1 | 0.14 |
| Ammonia (µg/L N) | 4.3 | 7.0 | 4.8 | 4.0 | 7.1 | 5.4 | 0.30 |
| Nitrate + nitrite (µg/L N) | 58.3 | 47.7 | 13.7 | 11.8 | 14.4 | 29.2 | 4.42 |
| Chlorophyll *a* (µg/L) | 0.6 | 0.6 | 1.0 | 1.0 | 1.1 | 0.9 | 0.04 |
| Phaeophytin *a* (µg/L) | 0.5 | 0.3 | 0.6 | 0.6 | 0.8 | 0.5 | 0.04 |

Table 4.–Karluk Lake zooplankton abundance (number/$m^2$), 2009.

| Taxon | Date | | | | | Seasonal average |
|---|---|---|---|---|---|---|
| | 8-May | 24-Jun | 15-Jul | 21-Aug | 18-Sep | |
| Copepods: | | | | | | |
| *Epischura* | 4,777 | - | 2,123 | 4,644 | 1,062 | 2,521 |
| Ovig. *Epischura* | - | - | - | - | - | - |
| *Diaptomus* | 5,175 | 27,734 | 9,023 | 43,126 | 127,720 | 42,556 |
| Ovig. *Diaptomus* | - | - | - | - | - | - |
| *Cyclops* | 583,068 | 257,696 | 202,229 | 543,524 | 422,771 | 401,858 |
| Ovig. *Cyclops* | - | 2,123 | 49,363 | 12,208 | 1,062 | 12,951 |
| *Harpaticus* | - | - | 531 | 1,194 | 1,194 | 584 |
| Nauplii | 34,236 | 27,203 | 66,879 | 347,665 | 127,057 | 120,608 |
| Total copepods: | 627,256 | 314,756 | 330,149 | 952,362 | 680,865 | 581,077 |
| Cladocerans: | | | | | | |
| *Bosmina* | 2,787 | 9,554 | 30,255 | 46,178 | 69,334 | 31,622 |
| Ovig. *Bosmina* | - | 2,521 | - | 2,919 | 7,099 | 2,508 |
| *Daphnia longiremis* | 6,237 | 19,639 | 52,548 | 57,059 | 82,338 | 43,564 |
| Ovig. *Daphnia longiremis* | 265 | 3,450 | 20,170 | 23,753 | 23,620 | 14,252 |
| *Holopedium* | - | - | 1,592 | 1,327 | - | 584 |
| Immature cladocerans | - | 26,805 | 74,841 | 54,671 | 32,710 | 37,805 |
| Total cladocerans: | 9,289 | 61,969 | 179,406 | 185,908 | 215,101 | 130,334 |
| Total Copepods + Cladocerans | 636,545 | 376,725 | 509,554 | 1,138,270 | 895,966 | 711,412 |

Table 5.–Karluk Lake seasonal zooplankton biomass (mg/m$^2$), 2009.

| Taxon | | Date | | | | | Seasonal weighted average |
|---|---|---|---|---|---|---|---|
| | | 8-May | 24-Jun | 15-Jul | 21-Aug | 18-Sep | |
| Copepods: | | | | | | | |
| | *Epischura* | 5 | - | 18 | 6 | 2 | 6 |
| | Ovig. *Epischura* | - | - | - | - | - | - |
| | *Diaptomus* | 19 | 181 | 86 | 132 | 270 | 137 |
| | Ovig. *Diaptomus* | - | - | - | - | - | - |
| | *Cyclops* | 1,142 | 1,046 | 878 | 995 | 482 | 908 |
| | Ovig. *Cyclops* | - | 11 | 266 | 67 | 12 | 71 |
| | *Harpaticus* | - | - | 1 | 1 | 2 | 1 |
| Total copepods: | | 1,166 | 1,238 | 1,249 | 1,201 | 767 | 1,124 |
| Cladocerans: | | | | | | | |
| | *Bosmina* | 5 | 18 | 54 | 73 | 91 | 48 |
| | Ovig. *Bosmina* | - | 7 | | 5 | 8 | 5 |
| | *Daphnia longiremis* | 9 | 37 | 83 | 78 | 95 | 60 |
| | Ovig. *Daphnia longiremis* | 2 | 13 | 89 | 57 | 58 | 44 |
| | *Holopedium* | - | - | 4 | 3 | - | 1 |
| | *Chydorinae* | - | - | - | - | - | - |
| Total cladocerans: | | 15 | 74 | 229 | 216 | 253 | 159 |
| Total Copepods + Cladocerans | | 1,181 | 1,312 | 1,478 | 1,418 | 1,020 | 1,283 |

Table 6.–Seasonal lengths (mm) of Karluk Lake zooplankton, 2009.

| Taxon | Date | | | | | Seasonal weighted average |
| --- | --- | --- | --- | --- | --- | --- |
| | 8-May | 24-Jun | 15-Jul | 21-Aug | 18-Sep | |
| Copepods: | | | | | | |
| *Epischura* | 0.59 | - | 0.99 | 0.63 | 0.55 | 0.67 |
| *Diaptomus* | 0.94 | 1.06 | 1.33 | 0.88 | 0.77 | 0.87 |
| *Cyclops* | 0.72 | 1.05 | 1.09 | 0.73 | 0.58 | 0.78 |
| Ovig. *Cyclops* | - | 1.18 | 1.21 | 1.21 | 1.22 | 1.21 |
| *Harpaticus* | - | - | 0.58 | 0.56 | 0.56 | 0.58 |
| Cladocerans: | | | | | | |
| *Bosmina* | 0.43 | 0.44 | 0.44 | 0.40 | 0.38 | 0.41 |
| Ovig. *Bosmina* | - | 0.54 | - | 0.44 | 0.35 | 0.41 |
| *Daphnia longiremis* | 0.56 | 0.66 | 0.60 | 0.57 | 0.54 | 0.57 |
| Ovig. *Daphnia longiremis* | 0.89 | 0.88 | 0.98 | 0.74 | 0.74 | 0.81 |
| *Holopedium* | - | - | 0.53 | 0.38 | - | 0.50 |

Table 7.–Frazer Lake zooplankton abundance (number/m$^2$), 2009.

| | Date | | | | | Seasonal |
|---|---|---|---|---|---|---|
| Taxon | 8-May | 20-Jun | 22-Jul | 19-Aug | 16-Sep | average |
| Copepods: | | | | | | |
| *Epischura* | - | - | 1,327 | 5,334 | 1,811 | 1,695 |
| Ovig. *Epischura* | - | - | - | - | - | - |
| *Diaptomus* | 265 | - | - | - | - | 53 |
| Ovig. *Diaptomus* | - | - | - | - | - | - |
| *Cyclops* | 71,921 | 51,088 | 112,527 | 11,916 | 9,156 | 51,322 |
| Ovig. *Cyclops* | - | - | 12,739 | 743 | - | 2,696 |
| *Harpaticus* | - | - | - | - | 1,307 | 261 |
| Nauplii | 57,590 | 8,692 | 1,592 | 16,534 | 7,670 | 18,416 |
| Total copepods: | 129,777 | 59,780 | 128,185 | 34,528 | 19,944 | 74,443 |
| Cladocerans: | | | | | | |
| *Bosmina* | 1,592 | 1,725 | 15,127 | 39,039 | 65,870 | 24,671 |
| Ovig. *Bosmina* | - | 531 | 5,042 | 1,141 | 3,915 | 2,126 |
| *Daphnia longiremis* | 4,512 | 929 | 19,108 | 46,338 | 91,143 | 32,406 |
| Ovig. *Daphnia longiremis* | - | 1,592 | 8,227 | 20,648 | 16,919 | 9,477 |
| *Holopedium* | - | - | 531 | 1,725 | - | 451 |
| Immature cladocerans | - | 3,450 | 4,246 | 24,841 | 30,819 | 12,671 |
| Total cladocerans: | 6,104 | 8,227 | 52,282 | 133,731 | 208,665 | 81,802 |
| Total Copepods + Cladocerans | 135,881 | 68,007 | 180,467 | 168,259 | 228,609 | 156,245 |

Table 8.–Frazer Lake weighted zooplankton biomass (mg/m$^2$), 2009.

| | Taxon | Date | | | | | Seasonal weighted average |
|---|---|---|---|---|---|---|---|
| | | 8-May | 20-Jun | 22-Jul | 19-Aug | 16-Sep | |
| Copepods: | | | | | | | |
| | *Epischura* | - | - | 13 | 5 | 15 | 7 |
| | Ovig. *Epischura* | - | - | - | - | - | - |
| | *Diaptomus* | 2 | - | - | - | - | - |
| | Ovig. *Diaptomus* | - | - | - | - | - | - |
| | *Cyclops* | 72 | 117 | 424 | 39 | 12 | 133 |
| | Ovig. *Cyclops* | - | - | 67 | 5 | - | 14 |
| | *Harpaticus* | - | - | - | - | 1 | 0 |
| Total copepods: | | 74 | 117 | 504 | 49 | 29 | 154 |
| Cladocerans: | | | | | | | |
| | *Bosmina* | 2 | 1 | 15 | 42 | 90 | 30 |
| | Ovig. *Bosmina* | - | 2 | - | 2 | 6 | 2 |
| | *Daphnia longiremis* | 6 | 1 | 20 | 40 | 81 | 29 |
| | Ovig. *Daphnia longiremis* | - | 8 | 25 | 43 | 30 | 21 |
| | *Holopedium* | - | - | 4 | 3 | - | 1 |
| | *Chydorinae* | - | - | - | - | - | - |
| Total cladocerans: | | 8 | 13 | 63 | 130 | 207 | 84 |
| Total Copepods + Cladocerans | | 82 | 130 | 567 | 179 | 236 | 238 |

Table 9.–Seasonal lengths of Frazer Lake zooplankton (mm), 2009.

| Taxon | Date | | | | | Seasonal weighted average |
|---|---|---|---|---|---|---|
| | 8-May | 20-Jun | 22-Jul | 19-Aug | 16-Sep | |
| Copepods: | | | | | | |
| *Epischura* | - | - | 1.33 | 0.56 | 0.98 | 0.77 |
| *Diaptomus* | 0.91 | - | - | - | - | 0.91 |
| *Cyclops* | 0.54 | 0.81 | 1.02 | 0.93 | 0.64 | 0.83 |
| Ovig. *Cyclops* | - | - | 1.19 | 1.33 | - | 1.20 |
| *Harpaticus* | - | - | - | - | 0.53 | 0.53 |
| Cladocerans: | | | | | | |
| *Bosmina* | 0.39 | 0.33 | 0.33 | 0.34 | 0.38 | 0.36 |
| Ovig. *Bosmina* | - | 0.48 | - | 0.40 | 0.40 | 0.44 |
| *Daphnia longiremis* | 0.54 | 0.48 | 0.50 | 0.47 | 0.47 | 0.48 |
| Ovig. *Daphnia longiremis* | - | 0.77 | 0.82 | 0.69 | 0.64 | 0.70 |
| *Holopedium* | - | - | 0.51 | 0.50 | - | 0.51 |

Table 10.–Sample size (N), mean, and standard deviation (SD) values of Karluk Lake surface temperature, dissolved oxygen, and turbidity by month and region, 2009.

| | Sample month | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | May | | | June | | | July | | | August | | | September | | |
| Karluk Lake | N | Mean | SD | N | Mean | SD | N | Mean | SD | N | Mean | SD | N | Mean | SD |
| Temperature ($^oC$) | | | | | | | | | | | | | | | |
| Upper | 8,968 | 5.48 | 0.09 | 9,500 | 9.60 | 0.05 | 4,537 | 15.63 | 0.10 | 2,486 | 13.70 | 0.63 | | ND | |
| Middle | 12,444 | 5.47 | 0.11 | 23,929 | 9.40 | 0.24 | 12,444 | 16.28 | 0.76 | 6,934 | 13.67 | 0.20 | 9,858 | 10.49 | 0.28 |
| Lower | 30,193 | 5.41 | 0.33 | 13,464 | 8.41 | 0.55 | 29,389 | 16.12 | 0.55 | 8,954 | 13.12 | 0.13 | 9,880 | 11.13 | 0.23 |
| Dissolved Oxygen (mg/L) | | | | | | | | | | | | | | | |
| Upper | 8,968 | 12.19 | 0.05 | 9,500 | 12.11 | 0.05 | 4,537 | 10.51 | 0.05 | 2,486 | 10.56 | 0.29 | | ND | |
| Middle | 12,444 | 12.20 | 0.04 | 23,929 | 12.19 | 0.07 | 25,517 | 10.61 | 0.09 | 6,934 | 10.51 | 0.07 | 9,858 | 10.68 | 0.04 |
| Lower | 30,193 | 12.19 | 0.13 | 13,464 | 12.26 | 0.05 | 29,389 | 10.63 | 0.10 | 8,954 | 10.56 | 0.04 | 9,880 | 10.63 | 0.02 |
| Turbidity (NTU) | | | | | | | | | | | | | | | |
| Upper | 4,339 | 1.3 | 0.65 | 5,044 | 1.5 | 0.75 | 2,266 | 1.5 | 1.04 | 1,179 | 1.3 | 0.6 | | ND | |
| Middle | 6,065 | 1.3 | 1.38 | 11,926 | 1.5 | 1.40 | 12,451 | 1.8 | 7.84 | 3,329 | 1.5 | 4.5 | 4,614 | 1.2 | 0.55 |
| Lower | 16,190 | 1.4 | 2.95 | 6,613 | 1.5 | 5.46 | 13,353 | 2.0 | 9.70 | 4,205 | 1.7 | 7.5 | 4,584 | 1.3 | 3.08 |

Table 11.–Sample size (N), mean, and standard deviation (SD) values of Frazer Lake surface temperature, dissolved oxygen, and turbidity by month and region, 2009.

| | Sample month | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | May | | | June | | | July | | | August | | | September | | |
| Frazer Lake | N | Mean | SD | N | Mean | SD | N | Mean | SD | N | Mean | SD | N | Mean | SD |
| Temperature (°C) | | | | | | | | | | | | | | | |
| Upper | ND | ND | ND | 12,322 | 9.28 | 0.33 | 7,034 | 15.23 | 0.29 | 7,088 | 12.80 | 0.22 | 11,852 | 9.86 | 0.62 |
| Middle | ND | ND | ND | 9,323 | 8.46 | 0.48 | 2,428 | 14.71 | 0.08 | 6,272 | 12.67 | 0.24 | 4,950 | 11.35 | 0.30 |
| Lower | ND | ND | ND | 6,449 | 7.03 | 0.35 | 1,616 | 13.86 | 0.21 | 9,096 | 12.59 | 0.13 | 7,408 | 11.66 | 0.05 |
| Dissolved Oxygen (mg/L) | | | | | | | | | | | | | | | |
| Upper | ND | ND | ND | 12,322 | 11.6 | 0.08 | 7,034 | 10.12 | 0.11 | 7,088 | 10.69 | 0.03 | 11,852 | 10.41 | 0.09 |
| Middle | ND | ND | ND | 9,323 | 11.8 | 0.09 | 2,428 | 10.35 | 0.03 | 6,272 | 10.71 | 0.03 | 4,950 | 10.56 | 0.21 |
| Lower | ND | ND | ND | 6,449 | 11.9 | 0.04 | 1,616 | 10.80 | 0.21 | 9,096 | 10.67 | 0.04 | 7,408 | 10.57 | 0.05 |
| Turbidity (NTU) | | | | | | | | | | | | | | | |
| Upper | ND | ND | ND | 5,784 | 1.2 | 0.88 | 3,573 | 1.8 | 11.84 | 3,508 | 1.3 | 1.18 | 5,443 | 1.6 | 8.33 |
| Middle | ND | ND | ND | 4,403 | 1.2 | 0.65 | 1,178 | 1.7 | 2.77 | 3,107 | 1.8 | 7.01 | 2,369 | 1.3 | 3.03 |
| Lower | ND | ND | ND | 3,135 | 1.2 | 1.22 | 839 | 1.3 | 0.76 | 4,391 | 2.5 | 22.6 | 3,559 | 1.2 | 1.04 |

Table 12.–Sample size (N), mean, and standard deviation (SD) values of Karluk Lake surface chlorophyll concentrations and pH by month and region, 2009.

| | Sample month | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | May | | | June | | | July | | | August | | | September | | |
| Karluk Lake | N | Mean | SD | N | Mean | SD | N | Mean | SD | N | Mean | SD | N | Mean | SD |
| Chlorophyll (µg/L) | | | | | | | | | | | | | | | |
| Upper | 6,170 | 2.19 | 0.05 | 6,617 | 2.27 | 1.54 | 628 | 1.05 | 2.07 | 276 | 3.97 | 19.43 | ND | ND | ND |
| Middle | 8,610 | 2.24 | 0.04 | 19,625 | 3.33 | 2.09 | 3,197 | 2.27 | 13.53 | 753 | 2.45 | 12.01 | 1,940 | 1.11 | 0.88 |
| Lower | 25,673 | 2.86 | 0.13 | 11,417 | 3.27 | 3.43 | 1,603 | 2.59 | 10.77 | 1,125 | 1.18 | 2.73 | 1,776 | 1.12 | 1.27 |
| pH | | | | | | | | | | | | | | | |
| Upper | 8,968 | 7.76 | 0.04 | 9,500 | 8.54 | 0.12 | 4,537 | 8.20 | 0.10 | 2,486 | 7.48 | 0.12 | ND | ND | ND |
| Middle | 12,444 | 7.74 | 0.09 | 23,929 | 8.58 | 0.14 | 25,517 | 8.10 | 0.18 | 6,934 | 7.76 | 0.09 | 9,858 | 7.79 | 0.09 |
| Lower | 30,193 | 7.63 | 0.17 | 13,464 | 8.21 | 0.29 | 29,389 | 8.10 | 0.18 | 8,954 | 8.03 | 0.15 | 9,880 | 7.86 | 0.10 |

Table 13.–Sample size (N), mean, and standard deviation (SD) values of Frazer Lake surface chlorophyll concentrations and pH by month and region, 2009.

| | Sample month | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | May | | | June | | | July | | | August | | | September | | |
| Frazer Lake | N | Mean | SD | N | Mean | SD | N | Mean | SD | N | Mean | SD | N | Mean | SD |
| Chlorophyll (µg/L) | | | | | | | | | | | | | | | |
| Upper | ND | ND | ND | 7,558 | 1.98 | 2.07 | 1,191 | 1.14 | 4.11 | 1,212 | 1.61 | 7.78 | 1,763 | 1.31 | 3.34 |
| Middle | ND | ND | ND | 5,794 | 2.01 | 1.43 | 1,179 | 1.65 | 2.76 | 1,097 | 3.38 | 16.18 | 1,192 | 1.55 | 6.64 |
| Lower | ND | ND | ND | 4,215 | 2.04 | 1.50 | 388 | 1.09 | 1.02 | 1,732 | 1.59 | 7.01 | 2,096 | 0.74 | 1.04 |
| pH | | | | | | | | | | | | | | | |
| Upper | ND | ND | ND | 12,322 | 7.49 | 0.08 | 7,034 | 7.81 | 0.15 | 7,088 | 7.91 | 0.12 | 11,852 | 7.22 | 0.09 |
| Middle | ND | ND | ND | 3,135 | 7.27 | 0.07 | 2,428 | 8.01 | 0.06 | 6,272 | 7.87 | 0.10 | 4,950 | 7.75 | 0.21 |
| Lower | ND | ND | ND | 6,449 | 7.27 | 0.06 | 1,616 | 8.15 | 0.48 | 9,096 | 7.88 | 0.21 | 7,408 | 7.87 | 0.05 |

Table 14.–Comparison of AUV and original bathymetry statistics for Karluk and Frazer lakes.

| | | Map version | |
|---|---|---|---|
| Lake | Bathymetry statistic | Original | AUV |
| Karluk | | | |
| | Area ($m^2$) | 39,400,000 | 38,600,000 |
| | Volume ($m^3$) | 1,920,000,000 | 1,776,000,000 |
| | Maximum depth (m) | 126.0 | 139.4 |
| | Average depth (m) | 48.6 | 40.3 |
| Frazer | | | |
| | Area ($m^2$) | 16,600,000 | 16,100,000 |
| | Volume ($m^3$) | 551,100,000 | 527,000,000 |
| | Maximum depth (m) | 58.9 | 63.4 |
| | Average depth (m) | 33.2 | 37.5 |

Table 15.–Comparison of AUV and traditional temperature data by month and depth within a one-kilometer sampling grid in Karluk Lake, 2009.

| | | | May | | June | | July | | August | | Sept | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Station | Depth (m) | | AUV | Traditional | AUV | Traditional | AUV | Traditional | AUV | Traditional | AUV | Traditional |
| Upper | | | | | | | | | | | | |
| | Surface | ° C | 5.5 | 4.2 | 9.6 | 9.5 | 15.5 | 15.4 | 14.0 | 13.3 | ND | 10.0 |
| | | SD | 0.07 | - | 0.05 | - | 0.12 | - | 0.11 | - | ND | - |
| | 1-m | ° C | ND | 4.1 | ND | 9.5 | 15.5 | 15.4 | 13.9 | 13.3 | ND | 9.8 |
| | | SD | ND | - | ND | - | 0.12 | - | 0.15 | - | ND | - |
| | 5-m | ° C | ND | 3.9 | ND | 9.3 | 15.4 | 15.0 | 13.4 | 13.3 | ND | 9.7 |
| | | SD | ND | - | ND | - | 0.13 | - | 0.29 | - | ND | - |
| Middle | | | | | | | | | | | | |
| | Surface | ° C | 5.4 | 3.9 | 9.0 | 9.1 | 16.0 | 15.4 | 13.2 | 13.2 | 10.8 | 10.6 |
| | | SD | 0.20 | - | 0.09 | - | 0.22 | - | 0.05 | - | 0.08 | - |
| | 1-m | ° C | ND | 3.8 | ND | 9.1 | 15.7 | 15.1 | 13.3 | 13.2 | ND | 10.6 |
| | | SD | ND | - | ND | - | 0.09 | - | 0.01 | - | ND | - |
| | 5-m | ° C | ND | 3.6 | ND | 9.1 | ND | 14.8 | 12.9 | 13.3 | ND | 10.4 |
| | | SD | ND | - | ND | - | ND | - | 0.28 | - | ND | - |
| Lower | | | | | | | | | | | | |
| | Surface | ° C | 4.7 | ND | 8.3 | ND | 16.1 | ND | 13.0 | ND | 11.3 | ND |
| | | SD | 0.04 | ND | 0.24 | ND | 0.29 | ND | 0.06 | ND | 0.03 | ND |
| | 1-m | ° C | ND | ND | ND | ND | 15.6 | ND | 13.0 | ND | 11.3 | ND |
| | | SD | ND | ND | ND | ND | 0.06 | ND | 0.04 | ND | 0.04 | ND |
| | 5-m | ° C | ND | ND | ND | ND | ND | ND | 13.0 | ND | ND | ND |
| | | SD | ND | ND | ND | ND | ND | ND | 0.03 | ND | ND | ND |

Table 16.–Comparison of AUV and traditional dissolved oxygen data by month and depth within a one-kilometer sampling grid in Karluk Lake, 2009.

| | | | May | | June | | July | | August | | Sept | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Station | Depth (m) | | AUV | Traditional | AUV | Traditional | AUV | Traditional | AUV | Traditional | AUV | Traditional |
| Upper | | | | | | | | | | | | |
| | Surface | mg/L | 12.2 | 10.3 | 12.1 | 11.3 | 10.6 | 9.8 | 10.4 | 10.4 | ND | 11.0 |
| | | SD | 0.05 | - | 0.02 | - | 0.07 | - | 0.06 | - | ND | - |
| | 1-m | mg/L | ND | 13.3 | ND | 11.7 | 10.6 | 10.0 | 10.5 | 10.1 | ND | 11.0 |
| | | SD | ND | - | ND | - | 0.11 | - | 0.08 | - | ND | - |
| | 5-m | mg/L | ND | 10.3 | ND | 11.80 | 10.56 | 10.10 | 10.53 | 9.7 | ND | 11.1 |
| | | SD | ND | - | ND | - | 0.09 | - | 0.08 | - | ND | - |
| Middle | | | | | | | | | | | | |
| | Surface | mg/L | 12.2 | 12.8 | 12.3 | 12.6 | 10.6 | 9.9 | 10.6 | 10.0 | 10.7 | 11.0 |
| | | SD | 0.08 | - | 0.02 | - | 0.07 | - | 0.03 | - | 0.05 | - |
| | 1-m | mg/L | ND | 13.3 | ND | 12.8 | 10.7 | 10.2 | 10.6 | 9.8 | ND | 10.8 |
| | | SD | ND | - | ND | - | 0.02 | - | 0.01 | - | ND | - |
| | 5-m | mg/L | ND | 13.6 | ND | 13.0 | ND | 10.1 | 10.6 | 9.6 | ND | 10.6 |
| | | SD | ND | - | ND | - | ND | - | 0.07 | - | ND | - |
| Lower | | | | | | | | | | | | |
| | Surface | mg/L | 11.9 | ND | 12.2 | ND | 10.6 | ND | 10.6 | ND | 10.6 | ND |
| | | SD | 0.02 | ND | 0.04 | ND | 0.03 | ND | 0.02 | ND | 0.01 | ND |
| | 1-m | mg/L | ND | ND | ND | ND | 10.6 | ND | 10.6 | ND | 10.6 | ND |
| | | SD | ND | ND | ND | ND | 0.02 | ND | 0.02 | ND | 0.01 | ND |
| | 5-m | mg/L | ND | ND | ND | ND | ND | ND | 10.5 | ND | ND | ND |
| | | SD | ND | ND | ND | ND | ND | ND | 0.01 | ND | ND | ND |

Table 17.–Comparison of AUV and traditional pH data by month and depth within a one-kilometer sampling grid in Karluk Lake, 2009.

| | | | May | | June | | July | | August | | Sept | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Station | Depth (m) | | AUV | Traditional | AUV | Traditional | AUV | Traditional | AUV | Traditional | AUV | Traditional |
| Upper | | | | | | | | | | | | |
| | Surface | | 7.78 | ND | 8.66 | ND | 8.29 | ND | 7.72 | ND | ND | ND |
| | | SD | 0.04 | ND | 0.02 | ND | 0.05 | ND | 0.09 | ND | ND | ND |
| | 1-m | | ND | 6.65 | ND | 7.41 | 8.34 | 7.13 | 7.74 | 7.15 | ND | 7.56 |
| | | SD | ND | - | ND | - | 0.04 | - | 0.08 | - | ND | - |
| | 5-m | | ND | ND | ND | ND | 8.34 | ND | 7.73 | ND | ND | ND |
| | | SD | ND | ND | ND | ND | 0.01 | ND | 0.07 | ND | ND | ND |
| Middle | | | | | | | | | | | | |
| | Surface | | 7.62 | ND | 8.58 | ND | 8.09 | ND | 7.97 | ND | 7.94 | ND |
| | | SD | 0.05 | ND | 0.04 | ND | 0.14 | ND | 0.05 | ND | 0.05 | ND |
| | 1-m | | ND | ND | ND | ND | 8.22 | ND | 7.86 | ND | ND | ND |
| | | SD | ND | ND | ND | ND | 0.02 | ND | 0.00 | ND | ND | ND |
| | 5-m | | ND | ND | ND | ND | ND | ND | 7.89 | ND | ND | ND |
| | | SD | ND | ND | ND | ND | ND | ND | 0.12 | ND | ND | ND |
| Lower | | | | | | | | | | | | |
| | Surface | | 7.36 | ND | 7.99 | ND | 8.20 | ND | 8.13 | ND | 7.91 | ND |
| | | SD | 0.02 | ND | 0.10 | ND | 0.03 | ND | 0.04 | ND | 0.05 | ND |
| | 1-m | | ND | ND | ND | ND | 8.28 | ND | 8.02 | ND | 7.95 | ND |
| | | SD | ND | ND | ND | ND | 0.05 | ND | 0.09 | ND | 0.04 | ND |
| | 5-m | | ND | ND | ND | ND | ND | ND | 8.03 | ND | ND | ND |
| | | SD | ND | ND | ND | ND | ND | ND | 0.02 | ND | ND | ND |

Table 18.–Comparison of AUV and traditional chlorophyll data by month and depth within a one-kilometer sampling grid in Karluk Lake, 2009.

| | | | May | | June | | July | | August | | Sept | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Station | Depth (m) | | AUV | Traditional | AUV | Traditional | AUV | Traditional | AUV | Traditional | AUV | Traditional |
| Upper | | | | | | | | | | | | |
| | Surface | µg/L | 2.16 | ND | 2.20 | ND | 0.95 | ND | 3.94 | ND | ND | ND |
| | | SD | 1.48 | ND | 1.48 | ND | 0.75 | ND | 24.02 | ND | ND | ND |
| | 1-m | µg/L | ND | 0.96 | ND | 1.92 | 0.40 | 0.32 | 0.20 | 0.32 | ND | 0.96 |
| | | SD | ND | - | ND | - | - | | - | - | ND | - |
| | 5-m | µg/L | ND | ND | ND | ND | ND | ND | 0.53 | ND | ND | ND |
| | | SD | ND | ND | ND | ND | ND | ND | 0.45 | ND | ND | ND |
| Middle | | | | | | | | | | | | |
| | Surface | µg/L | 3.01 | ND | 4.69 | ND | 1.82 | ND | 1.05 | ND | 1.32 | ND |
| | | SD | 1.76 | ND | 2.18 | ND | 6.75 | ND | 0.94 | ND | 1.95 | ND |
| | 1-m | µg/L | ND | ND | ND | ND | 1.00 | ND | ND | ND | ND | ND |
| | | SD | ND | ND | ND | ND | 0.85 | ND | ND | ND | ND | ND |
| | 5-m | µg/L | ND | ND | ND | ND | ND | ND | 0.20 | ND | ND | ND |
| | | SD | ND | ND | ND | ND | ND | ND | - | ND | ND | ND |
| Lower | | | | | | | | | | | | |
| | Surface | µg/L | 2.42 | ND | 2.81 | ND | 5.55 | ND | 1.00 | ND | 1.04 | ND |
| | | SD | 1.91 | ND | 1.70 | ND | 18.85 | ND | 0.87 | ND | 0.89 | ND |
| | 1-m | µg/L | ND | ND | ND | ND | 1.03 | ND | ND | ND | 1.12 | ND |
| | | SD | ND | ND | ND | ND | 0.69 | ND | ND | ND | 0.98 | ND |
| | 5-m | µg/L | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| | | SD | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |

Table 19.–Comparison of AUV and traditional temperature data by month and depth within a one-kilometer sampling grid in Frazer Lake, 2009.

| | | | May | | June | | July | | August | | Sept | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Station | Depth (m) | | AUV | Traditional | AUV | Traditional | AUV | Traditional | AUV | Traditional | AUV | Traditional |
| Upper | | | | | | | | | | | | |
| | Surface | °C | ND | 3.2 | 9.3 | 9.3 | 15.2 | 15.1 | 13.1 | 12.7 | 10.2 | 10.2 |
| | | SD | ND | ND | 0.13 | ND | 0.06 | ND | 0.17 | ND | 0.11 | ND |
| | 1-m | °C | ND | 3.1 | 9.3 | 9.1 | ND | 15.2 | ND | 12.6 | ND | 10.2 |
| | | SD | ND | ND | 0.04 | ND | ND | ND | ND | ND | ND | ND |
| | 5-m | °C | ND | 3.0 | 9.0 | 8.6 | ND | 15.1 | ND | 12.6 | ND | 10.2 |
| | | SD | ND | ND | 0.24 | ND | ND | ND | ND | ND | ND | ND |
| Middle | | | | | | | | | | | | |
| | Surface | °C | ND | ND | 8.3 | ND | 14.7 | ND | 12.9 | ND | 11.1 | ND |
| | | SD | ND | ND | 0.21 | ND | 0.03 | ND | 0.12 | ND | 0.07 | ND |
| | 1-m | °C | ND | ND | 8.5 | ND | ND | ND | ND | ND | 11.0 | ND |
| | | SD | ND | ND | 0.03 | ND | ND | ND | ND | ND | 0.02 | ND |
| | 5-m | °C | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| | | SD | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Lower | | | | | | | | | | | | |
| | Surface | °C | ND | 3.7 | 7.1 | 7.9 | ND | 14.2 | 12.5 | 10.2 | 11.7 | 11.4 |
| | | SD | ND | ND | 0.17 | ND | ND | ND | 0.08 | ND | 0.03 | ND |
| | 1-m | °C | ND | 3.6 | 7.2 | 7.9 | ND | 14.2 | 12.5 | 10.1 | 11.6 | 11.4 |
| | | SD | ND | ND | 0.06 | ND | ND | ND | 0.02 | ND | 0.01 | ND |
| | 5-m | °C | ND | 3.5 | 7.3 | 7.7 | ND | 14.0 | 12.2 | 10.2 | 11.6 | 11.4 |
| | | SD | ND | ND | ND | ND | ND | ND | 0.04 | ND | 0.01 | ND |

Table 20.–Comparison of AUV and traditional dissolved oxygen data by month and depth within a one-kilometer sampling grid in Frazer Lake, 2009.

| | | | May | | June | | July | | August | | Sept | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Station | Depth (m) | | AUV | Traditional | AUV | Traditional | AUV | Traditional | AUV | Traditional | AUV | Traditional |
| Upper | | | | | | | | | | | | |
| | Surface | µg/L | ND | 13.2 | 11.6 | 14.9 | 10.1 | 10.3 | 10.7 | 10.3 | 10.4 | 11.1 |
| | | SD | ND | ND | 0.04 | ND | 0.03 | ND | 0.02 | ND | 0.01 | ND |
| | 1-m | µg/L | ND | 13.4 | 11.5 | 15.5 | ND | 9.8 | ND | 10.2 | ND | 11.1 |
| | | SD | ND | ND | 0.01 | ND | ND | ND | ND | ND | ND | ND |
| | 5-m | µg/L | ND | 13.0 | 11.6 | 13.4 | ND | 9.3 | ND | 9.9 | ND | 11.1 |
| | | SD | ND | ND | 0.01 | ND | ND | ND | ND | ND | ND | ND |
| Middle | | | | | | | | | | | | |
| | Surface | µg/L | ND | ND | 11.8 | ND | 10.3 | ND | 10.7 | ND | 10.5 | ND |
| | | SD | ND | ND | 0.04 | ND | 0.49 | ND | 0.02 | ND | 0.03 | ND |
| | 1-m | µg/L | ND | ND | 11.7 | ND | ND | ND | ND | ND | 10.5 | ND |
| | | SD | ND | ND | 0.01 | ND | ND | ND | ND | ND | 0.02 | ND |
| | 5-m | µg/L | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| | | SD | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Lower | | | | | | | | | | | | |
| | Surface | µg/L | ND | 13.0 | 11.9 | 13.9 | ND | 10.7 | 10.7 | 10.2 | 10.6 | 10.7 |
| | | SD | ND | ND | 0.02 | ND | ND | ND | 0.02 | ND | 0.02 | ND |
| | 1-m | µg/L | ND | 13.0 | 11.9 | 14.0 | ND | 10.2 | 10.7 | 10.1 | 10.6 | 10.7 |
| | | SD | ND | ND | 0.01 | ND | ND | ND | 0.02 | ND | 0.01 | ND |
| | 5-m | µg/L | ND | 13.1 | 11.9 | 13.6 | ND | 9.6 | 10.7 | 9.7 | 10.6 | 10.7 |
| | | SD | ND | ND | ND | ND | ND | ND | 0.01 | ND | 0.01 | ND |

Table 21.–Comparison of AUV and traditional pH data by month and depth within a one-kilometer sampling grid in Frazer Lake, 2009.

| | | | May | | June | | July | | August | | Sept | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Station | Depth (m) | | AUV | Traditional | AUV | Traditional | AUV | Traditional | AUV | Traditional | AUV | Traditional |
| Upper | | | | | | | | | | | | |
| | Surface | | ND | ND | 7.53 | ND | 7.90 | ND | 8.00 | ND | 7.25 | ND |
| | | SD | ND | ND | 0.04 | ND | 0.03 | ND | 0.02 | ND | 0.02 | ND |
| | 1-m | | ND | ND | 7.42 | ND | ND | ND | ND | ND | ND | ND |
| | | SD | ND | ND | 0.02 | ND | ND | ND | ND | ND | ND | ND |
| | 5-m | | ND | ND | 7.51 | ND | ND | ND | ND | ND | ND | ND |
| | | SD | ND | ND | 0.02 | ND | ND | ND | ND | ND | ND | ND |
| Middle | | | | | | | | | | | | |
| | Surface | | ND | ND | 7.49 | ND | 7.96 | ND | 7.87 | ND | 7.56 | ND |
| | | SD | ND | ND | 0.11 | ND | 0.39 | ND | 0.06 | ND | 0.02 | ND |
| | 1-m | | ND | ND | 7.46 | ND | ND | ND | ND | ND | 7.59 | ND |
| | | SD | ND | ND | 0.02 | ND | ND | ND | ND | ND | 0.01 | ND |
| | 5-m | N | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| | | SD | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Lower | | | | | | | | | | | | |
| | Surface | | ND | ND | 7.21 | ND | ND | ND | 7.90 | ND | 7.85 | ND |
| | | SD | ND | ND | 0.06 | ND | ND | ND | 0.09 | ND | 0.05 | ND |
| | 1-m | | ND | 6.82 | 7.12 | 6.92 | ND | 7.09 | 7.90 | 6.85 | 8.02 | 7.42 |
| | | SD | ND | ND | 0.01 | ND | ND | ND | 0.02 | ND | 0.01 | ND |
| | 5-m | | ND | ND | 7.11 | ND | ND | ND | 7.91 | ND | 8.00 | ND |
| | | SD | ND | ND | ND | ND | ND | ND | 0.01 | ND | 0.01 | ND |

Table 22.–Comparison of AUV and traditional chlorophyll data by month and depth within a one-kilometer sampling grid in Frazer Lake, 2009.

| | | | May | | June | | July | | August | | Sept | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Station | Depth (m) | | AUV | Traditional | AUV | Traditional | AUV | Traditional | AUV | Traditional | AUV | Traditional |
| Upper | | | | | | | | | | | | |
| | Surface | µg/L | ND | ND | 2.01 | ND | 1.23 | ND | 0.86 | ND | 1.09 | ND |
| | | SD | ND | ND | 1.42 | ND | 2.18 | ND | 0.78 | ND | 1.13 | ND |
| | 1-m | µg/L | ND | ND | 2.29 | ND | ND | ND | ND | ND | ND | ND |
| | | SD | ND | ND | 1.64 | ND | ND | ND | ND | ND | ND | ND |
| | 5-m | µg/L | ND | ND | 2.77 | ND | ND | ND | ND | ND | ND | ND |
| | | SD | ND | ND | 1.95 | ND | ND | ND | ND | ND | ND | ND |
| Middle | | | | | | | | | | | | |
| | Surface | µg/L | ND | ND | 1.97 | ND | 1.09 | ND | 6.42 | ND | 1.23 | ND |
| | | SD | ND | ND | 1.38 | ND | 0.89 | ND | 23.19 | ND | 1.51 | ND |
| | 1-m | µg/L | ND | ND | 2.32 | ND | ND | ND | ND | ND | 1.19 | ND |
| | | SD | ND | ND | 1.67 | ND | ND | ND | ND | ND | 0.83 | ND |
| | 5-m | µg/L | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| | | SD | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Lower | | | | | | | | | | | | |
| | Surface | µg/L | ND | ND | 1.99 | ND | ND | ND | 1.04 | ND | 1.13 | ND |
| | | SD | ND | ND | 1.40 | ND | ND | ND | 0.89 | ND | 0.91 | ND |
| | 1-m | µg/L | ND | 0.64 | 1.91 | 0.64 | ND | 0.96 | ND | 0.96 | 1.36 | 1.12 |
| | | SD | ND | ND | 1.55 | ND | ND | ND | ND | ND | 1.66 | ND |
| | 5-m | µg/L | ND | ND | 4.20 | ND | ND | ND | 1.98 | ND | 0.94 | ND |
| | | SD | ND | ND | ND | ND | ND | ND | 2.70 | ND | 0.67 | ND |

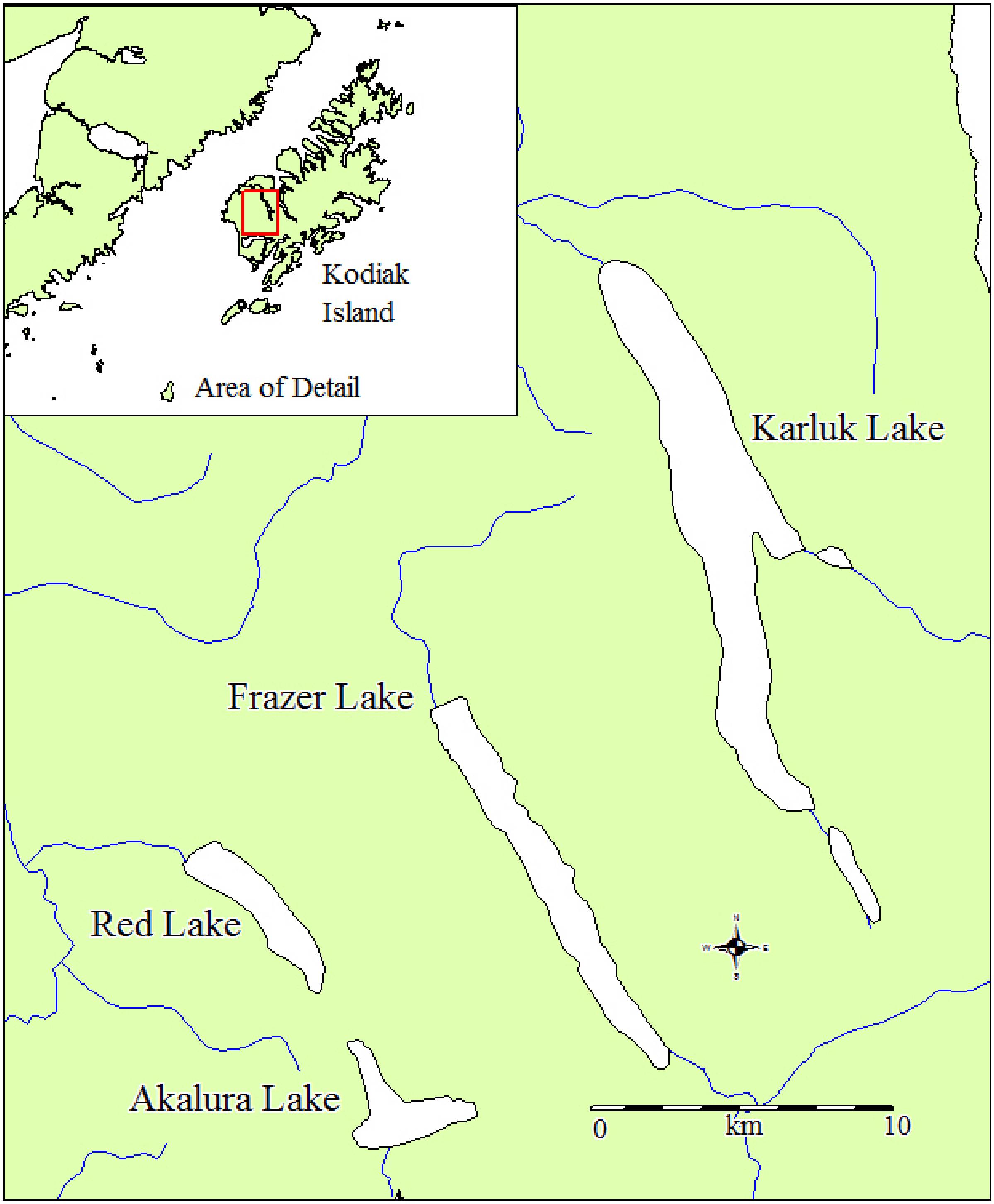



Figure 1.–Map of Karluk and Frazer lakes on Kodiak Island, Alaska.

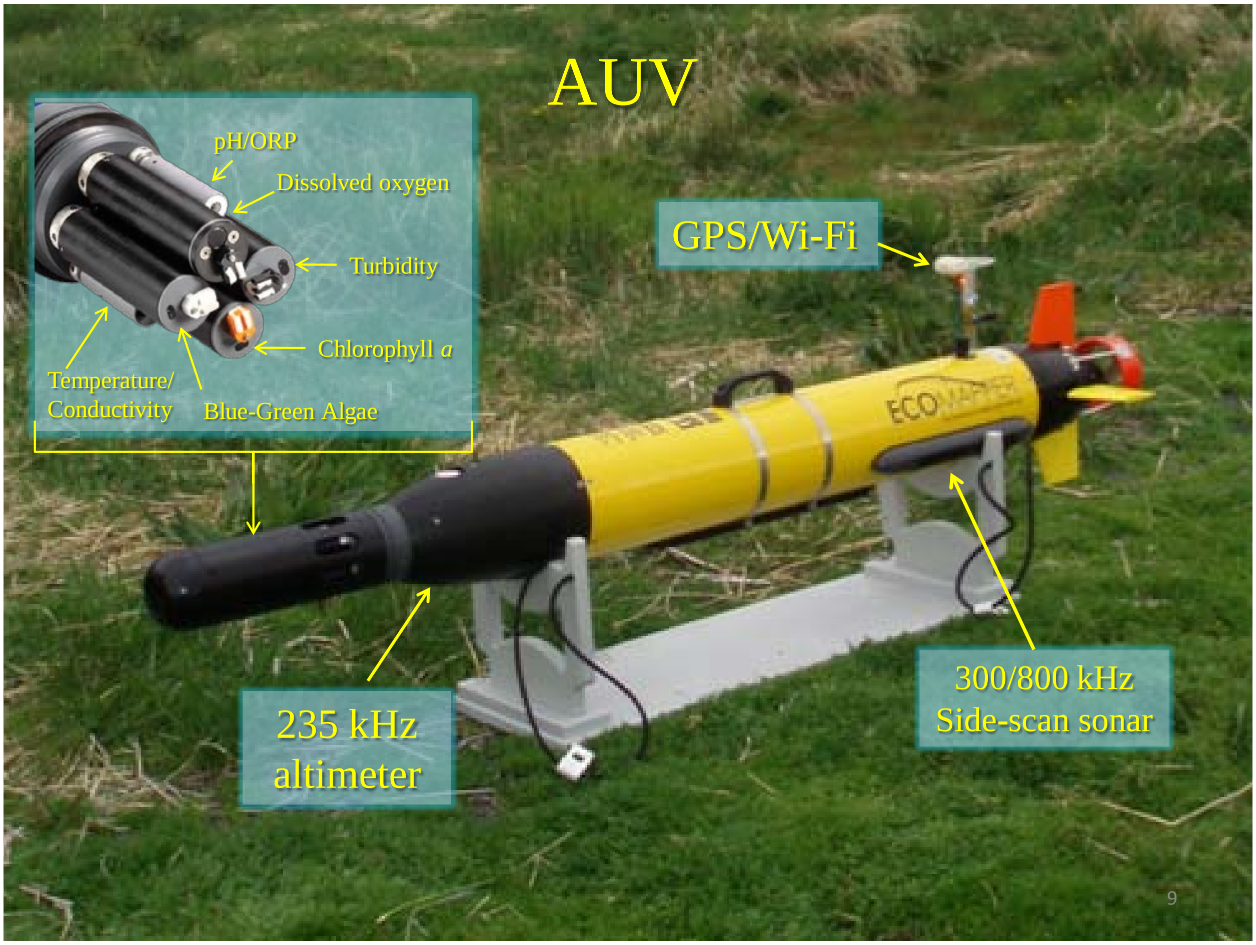



Figure 2.–Image of the AUV and its features.

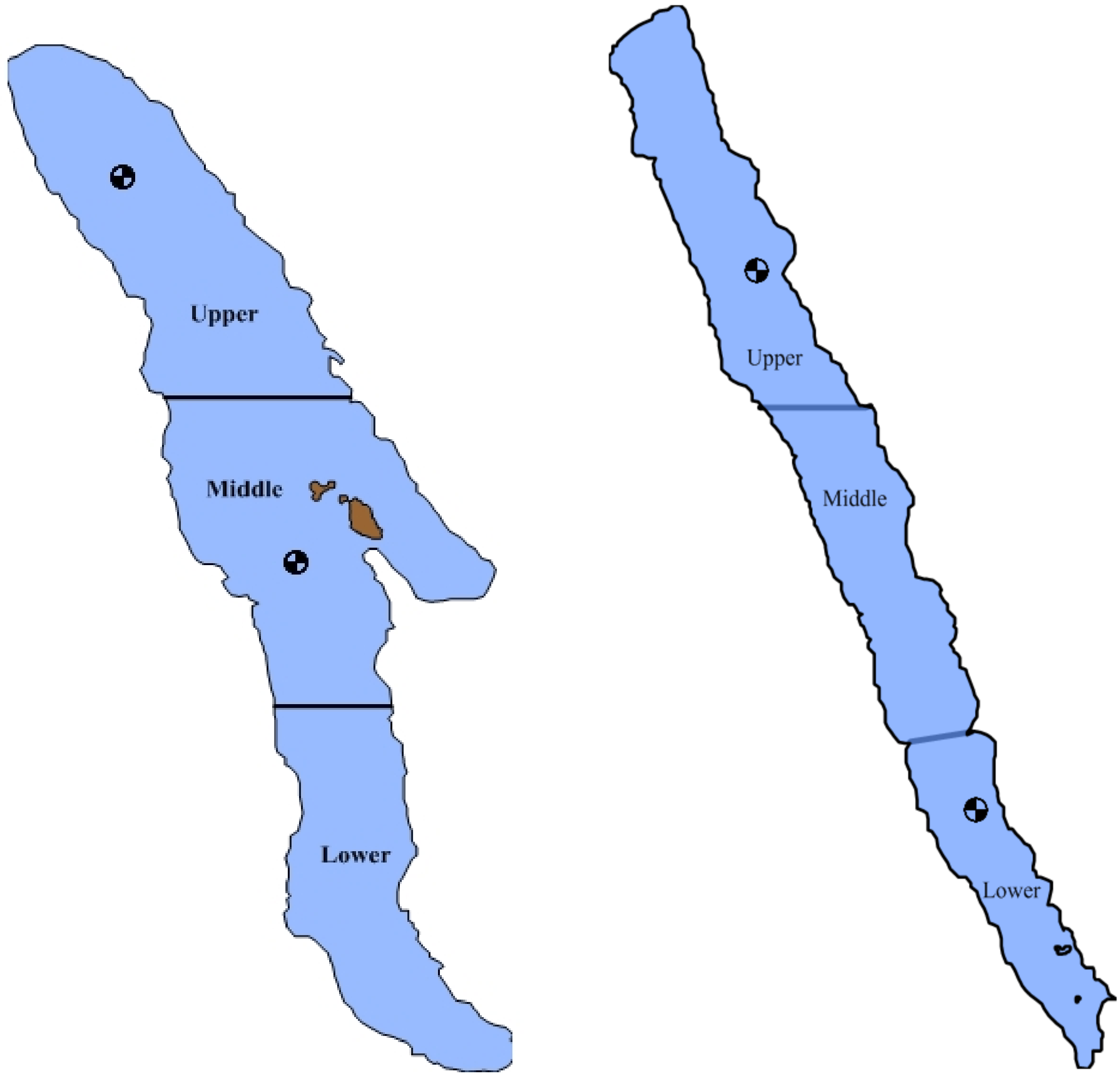



Figure 3.–Maps of Karluk (left) and Frazer (right) lakes and the locations of their limnology sampling stations and data sections.

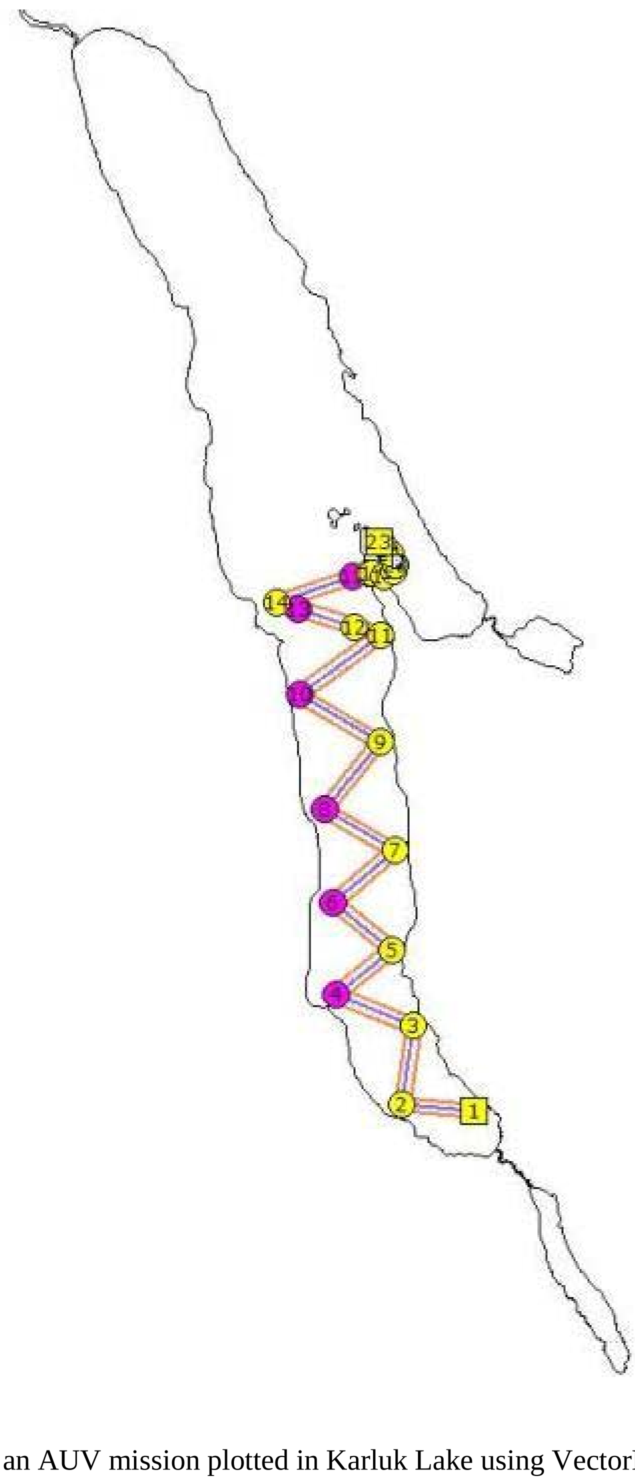


Figure 4.–Example of an AUV mission plotted in Karluk Lake using VectorMap software.

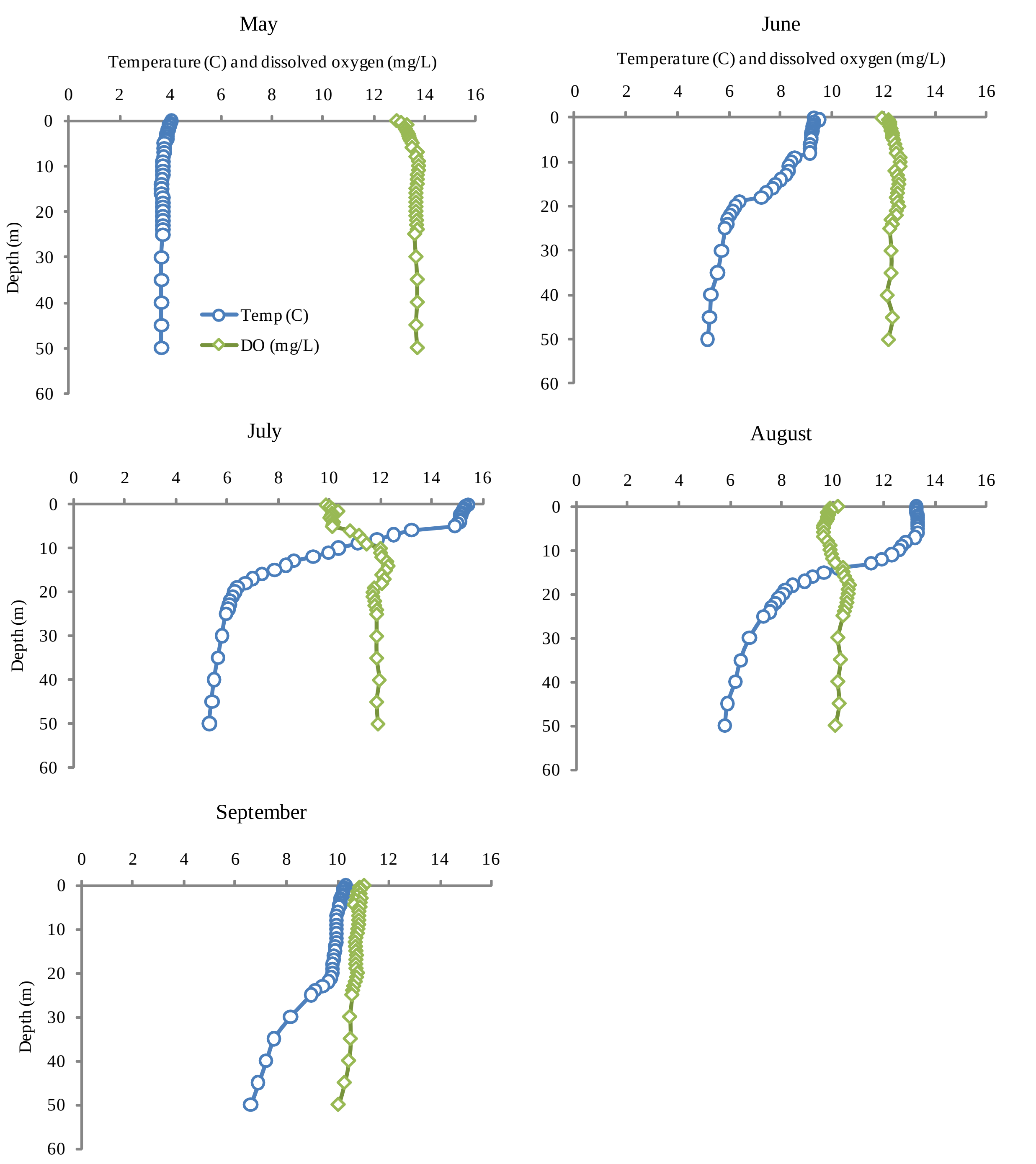



Figure 5.–Temperature and dissolved oxygen depth profiles by month for Karluk Lake, 2009.

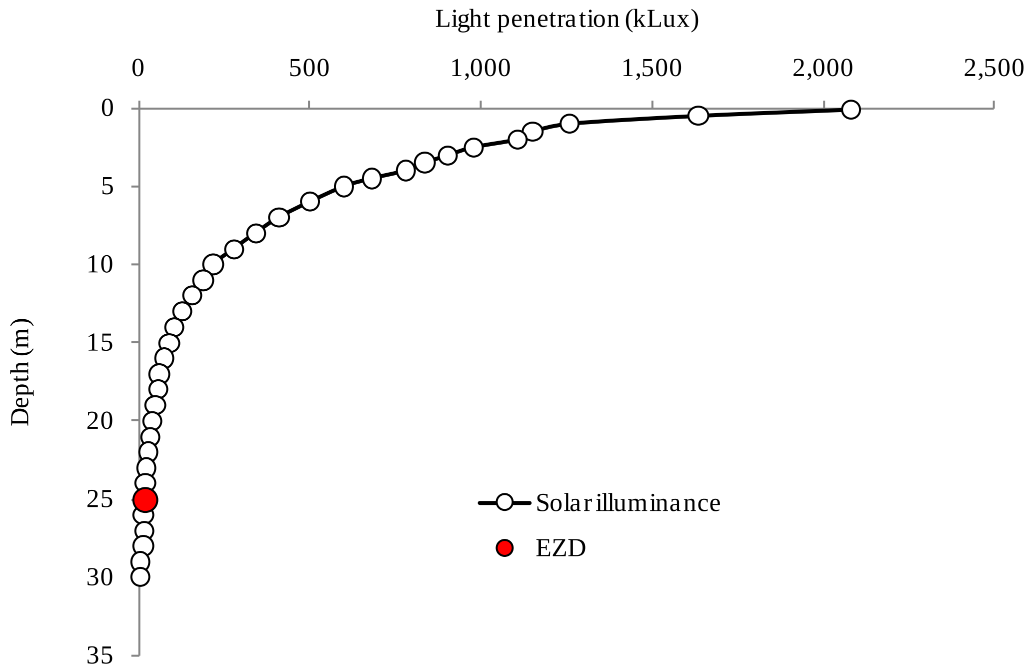



Figure 6.–Seasonal average light penetration and euphotic zone depth (EZD) for Karluk Lake, 2009.

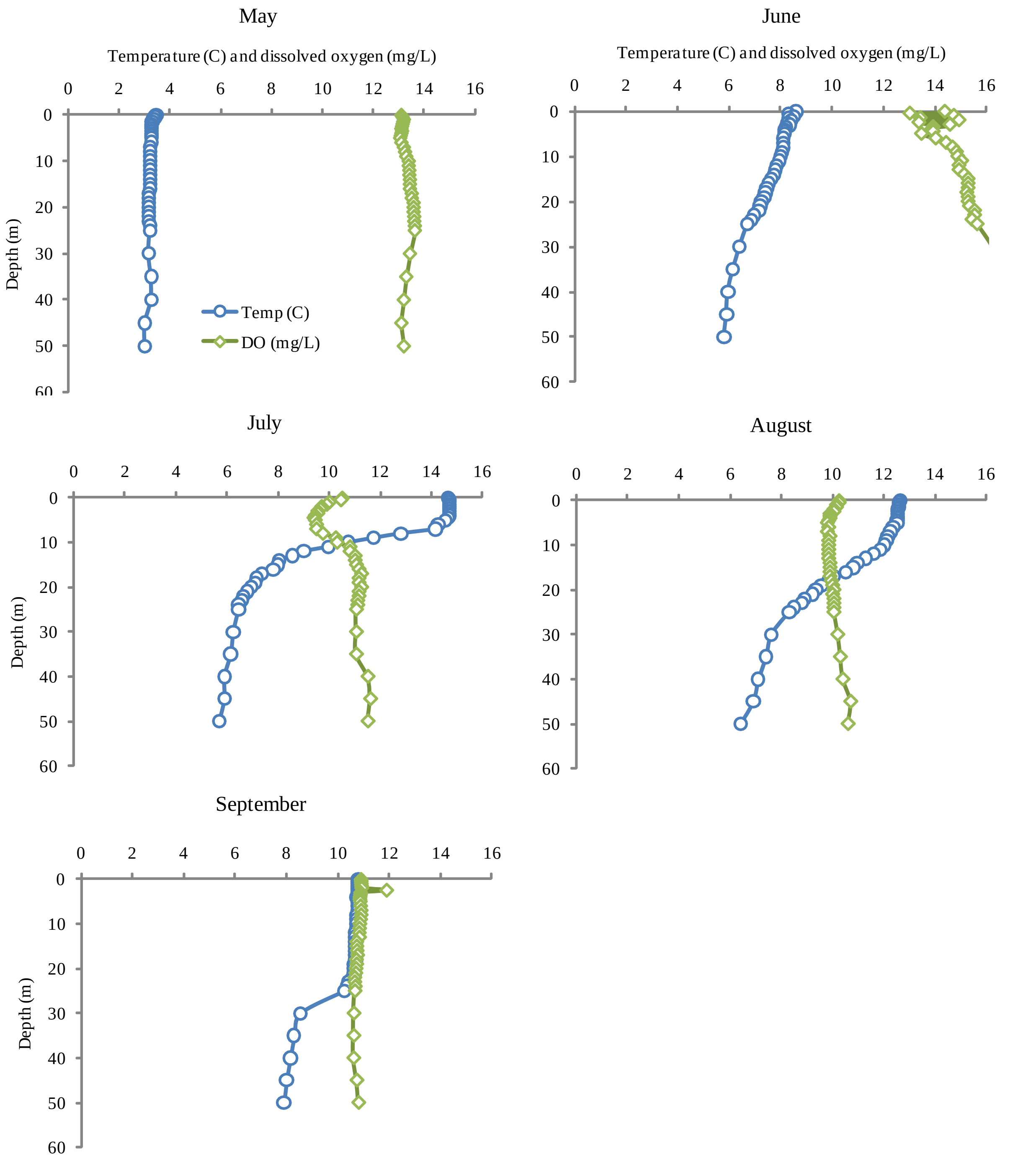



Figure 7.–Temperature and dissolved oxygen depth profiles by month for Frazer Lake, 2009.

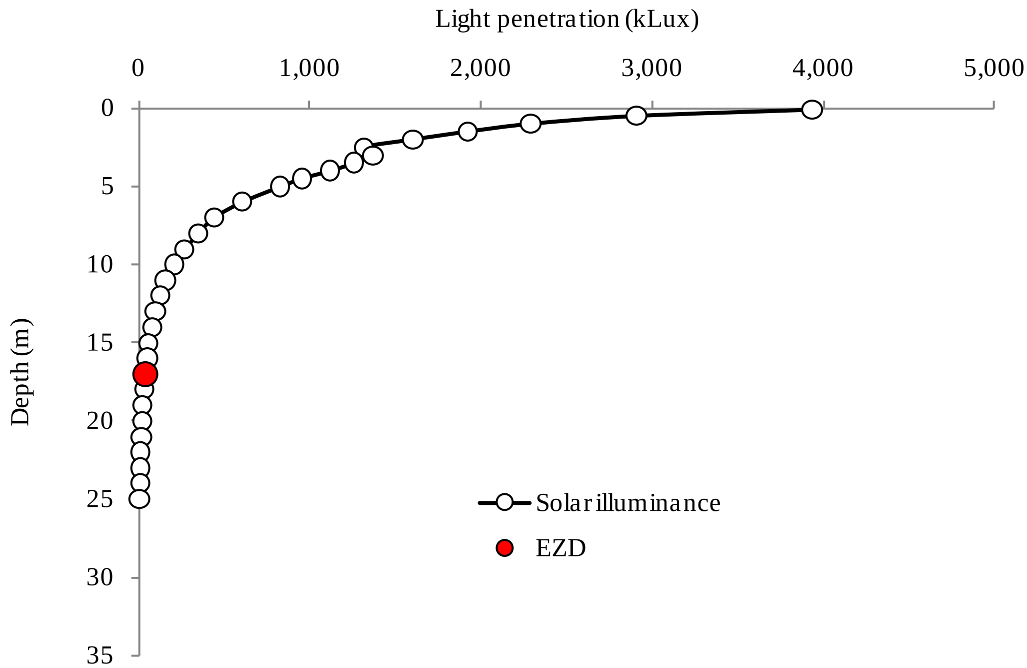



Figure 8.–Seasonal average light penetration and euphotic zone depth (EZD) for Frazer Lake, 2009.

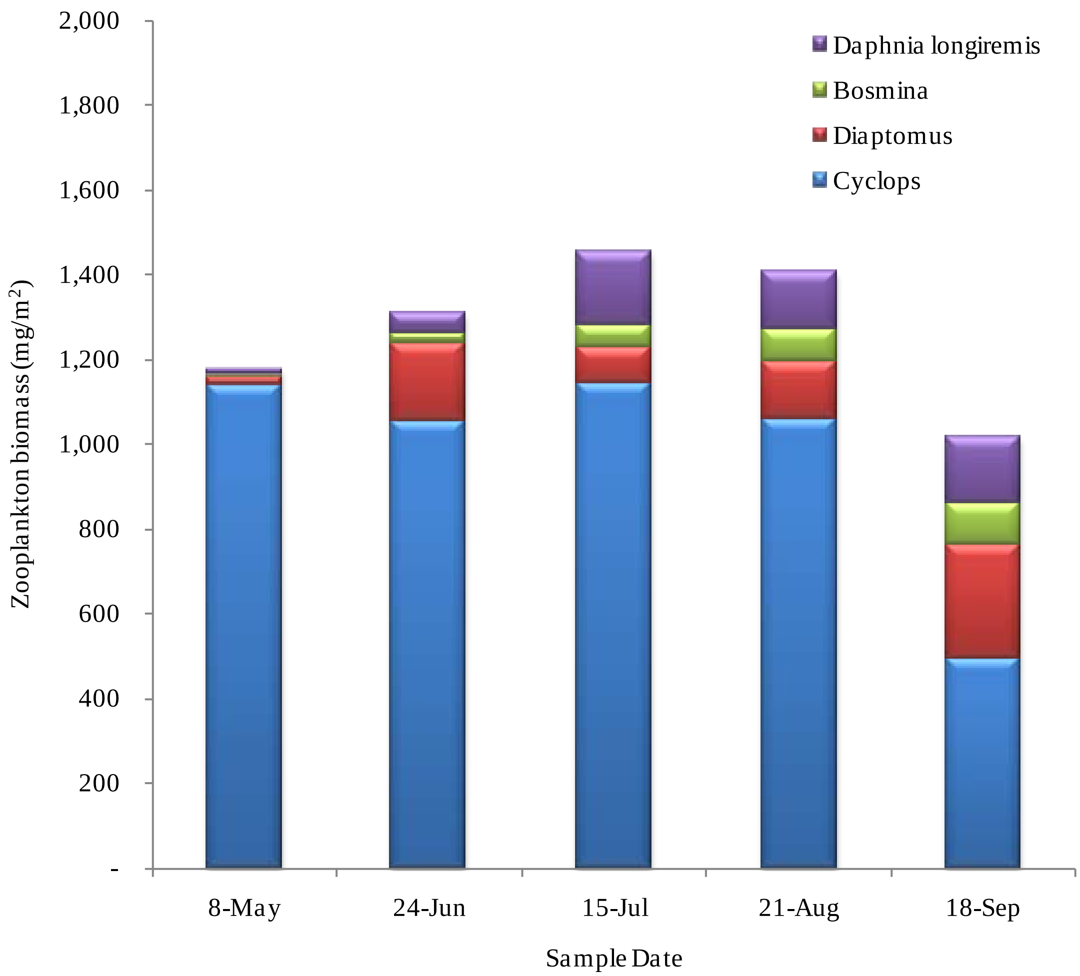



Figure 9.–Karluk Lake weighted zooplankton biomass (mg/m$^2$) by sample date in 2009 for the major copepod and cladoceran taxa. Biomass estimates include ovigerous zooplankton.

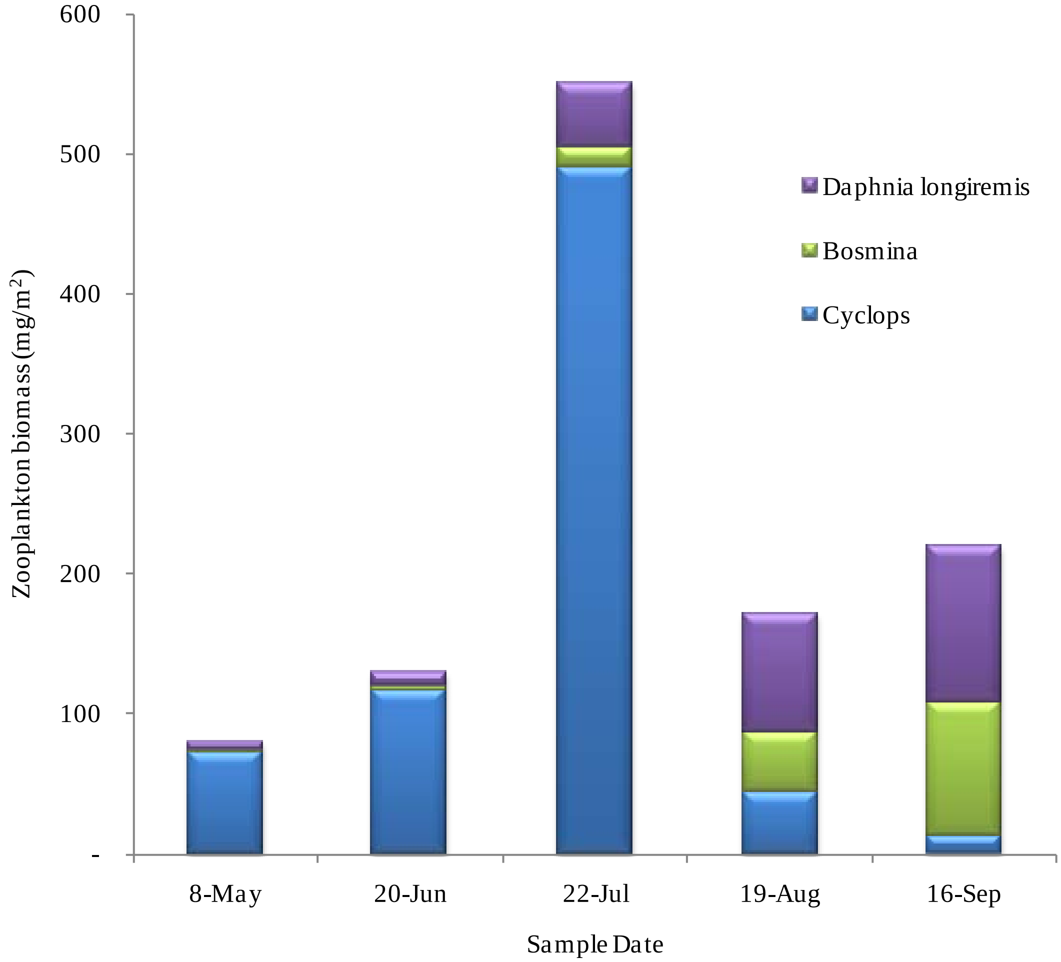



Figure 10.–Frazer Lake weighted zooplankton biomass (mg/m$^2$) by sample date in 2009 for the major copepod and cladoceran taxa. Biomass estimates include ovigerous zooplankton.

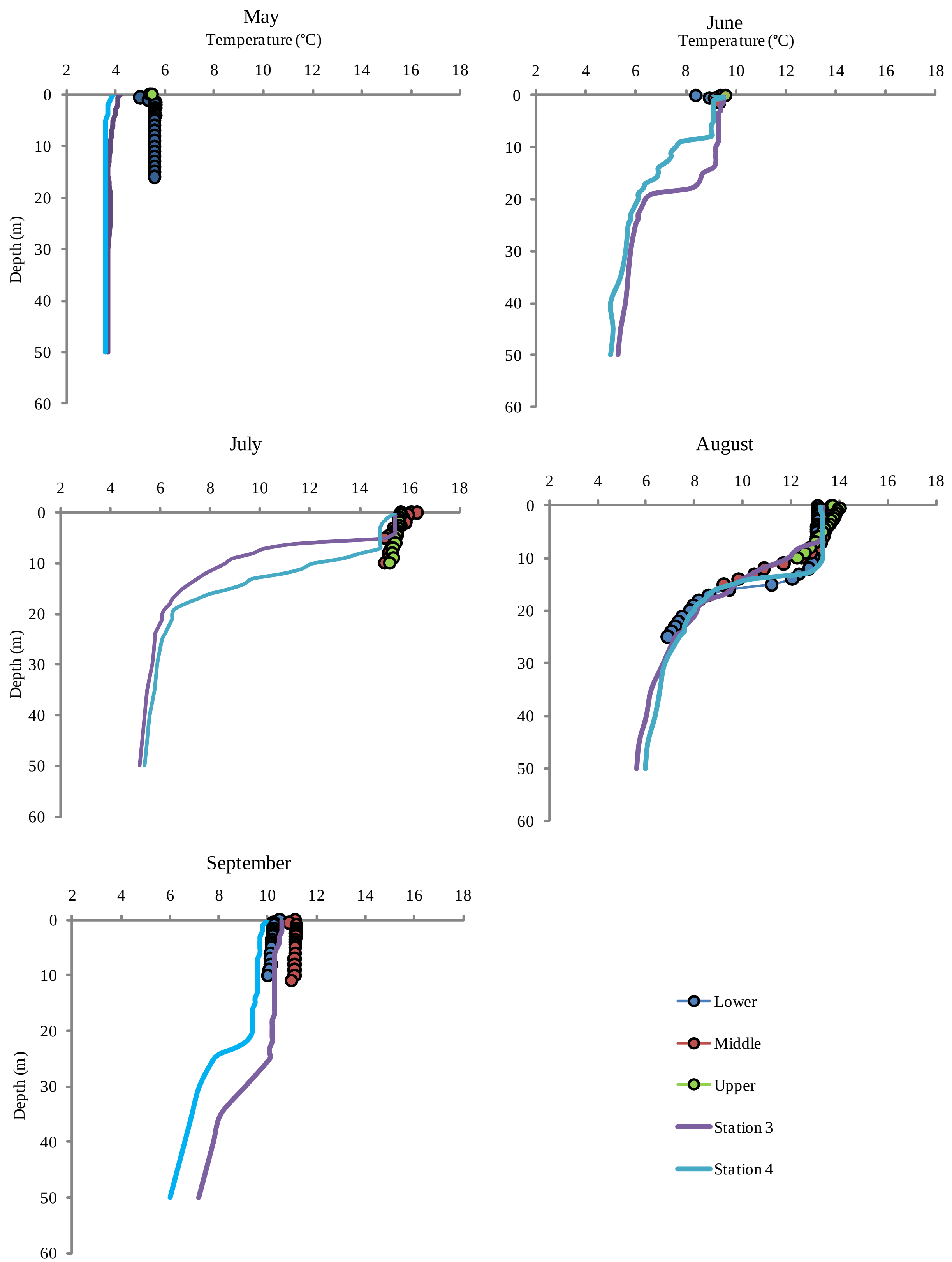



Figure 11.–Karluk Lake AUV temperature depth profiles by region and month compared to traditionally collected data, 2009.

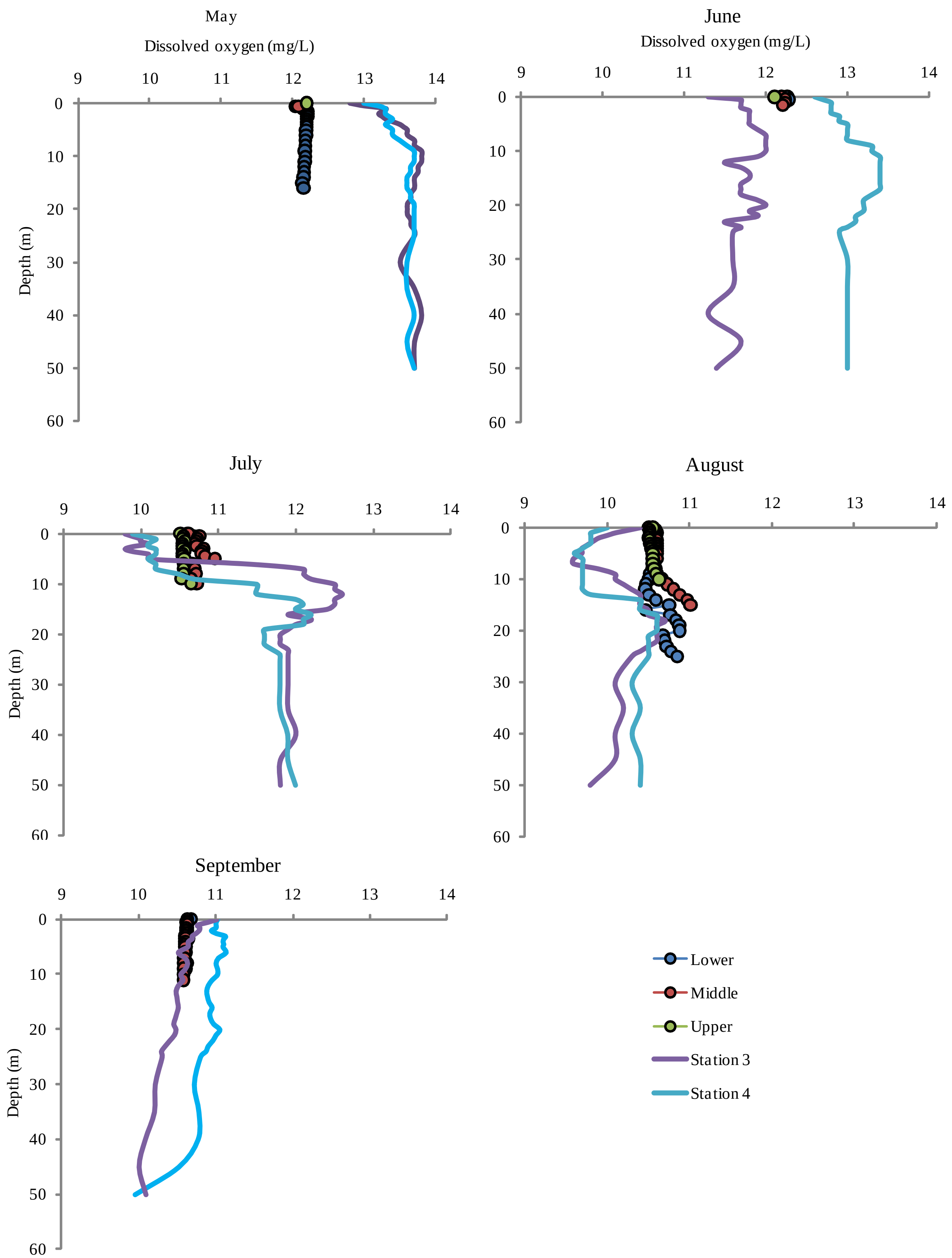



Figure 12.–Karluk Lake AUV dissolved oxygen depth profiles by region and month compared to traditionally collected data, 2009.

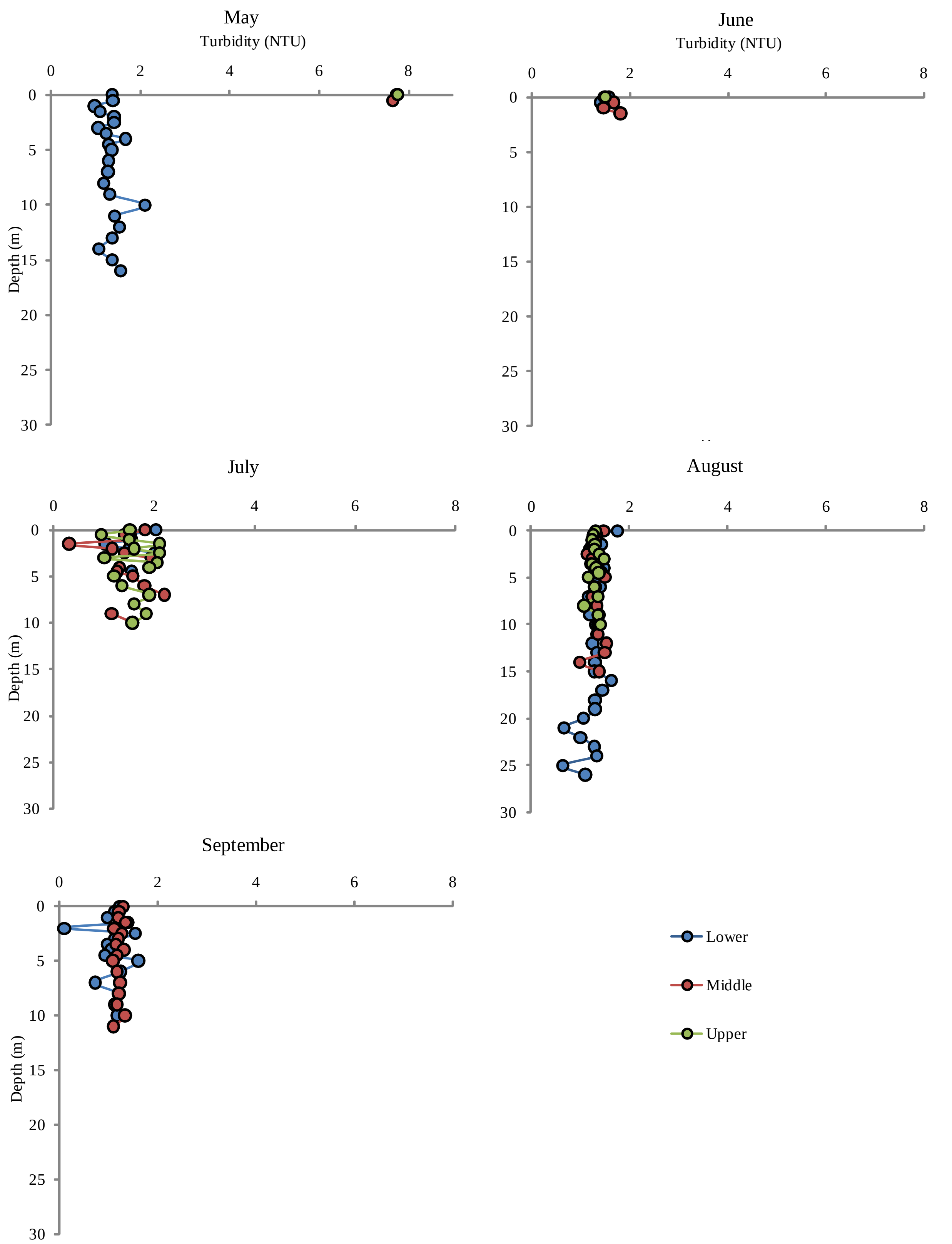



Figure 13.–Karluk Lake AUV turbidity depth profiles by region and month, 2009.

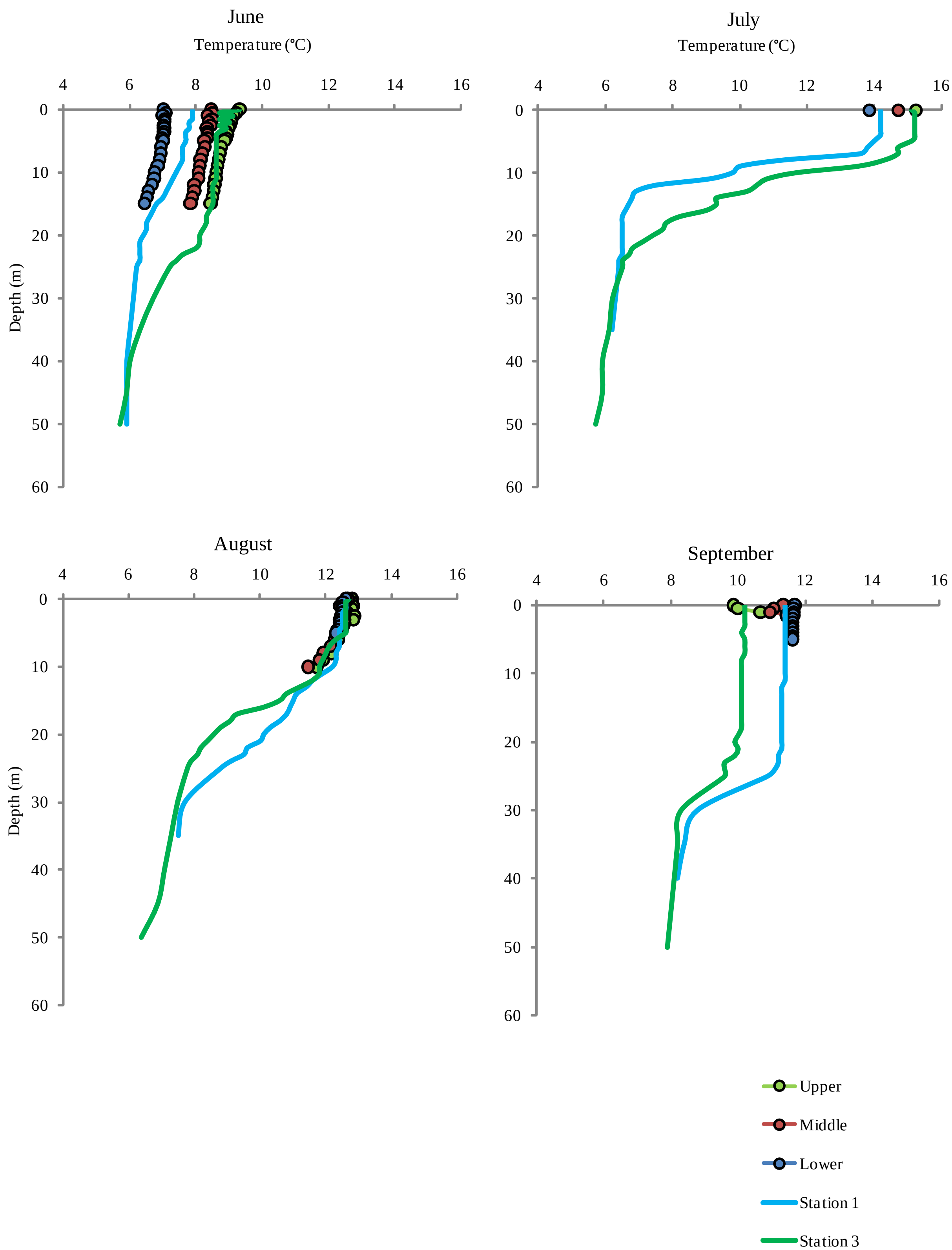



Figure 14.–Frazer Lake AUV temperature depth profiles by region and month compared to traditionally collected data, 2009.

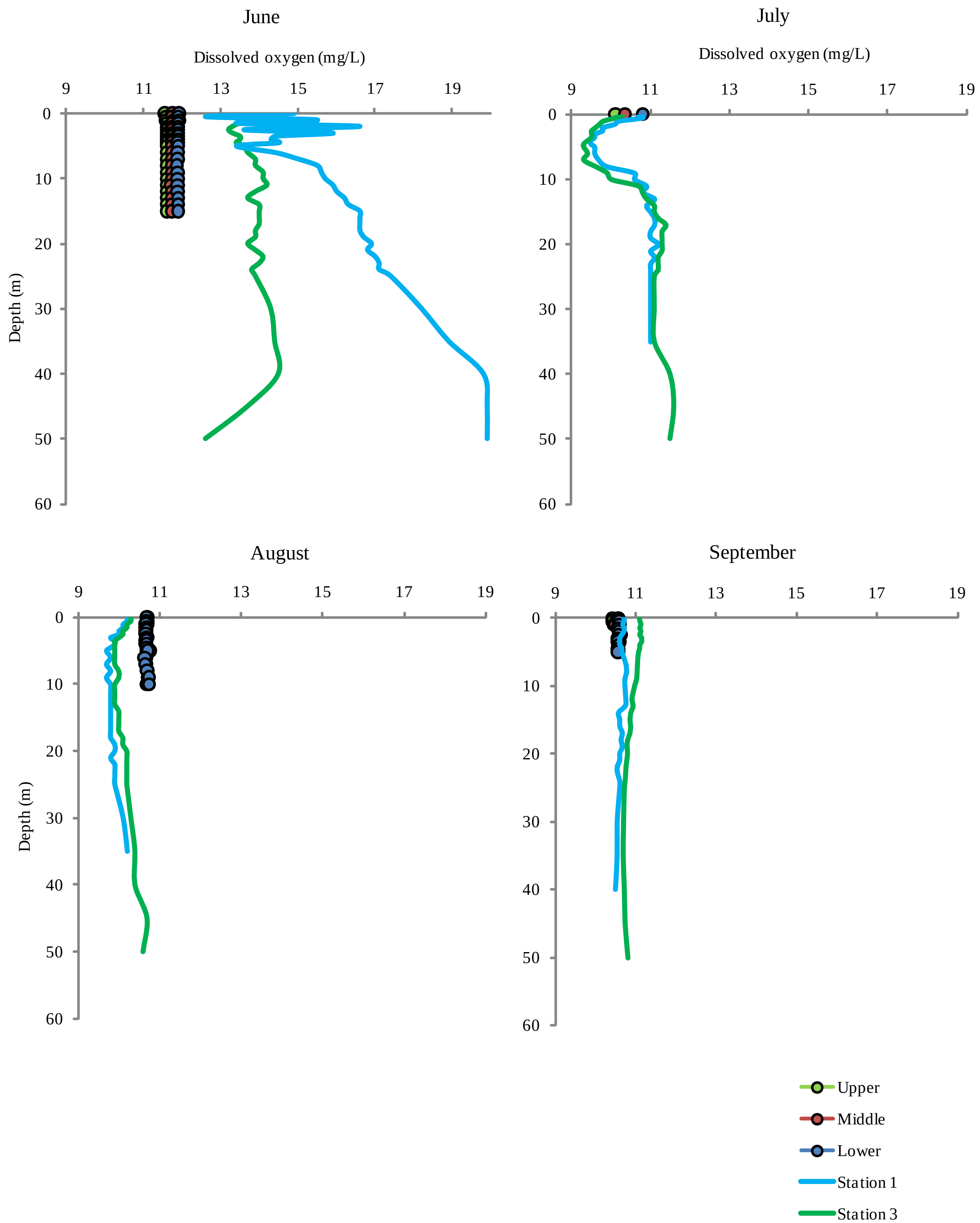



Figure 15.–Frazer Lake AUV dissolved oxygen depth profiles by region and month compared to traditionally collected data, 2009.

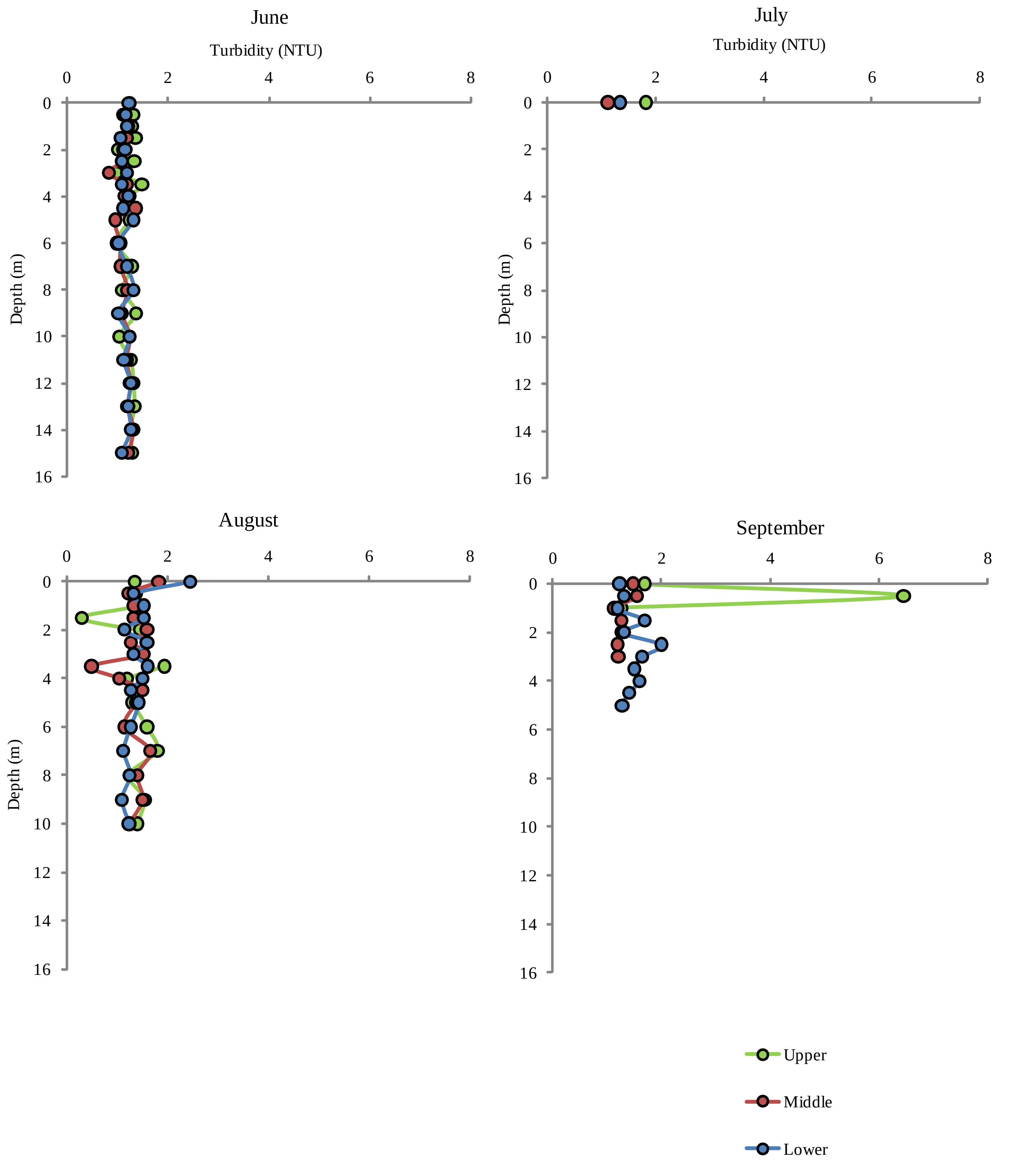



Figure 16.–Frazer Lake AUV turbidity depth profiles by region and month, 2009.

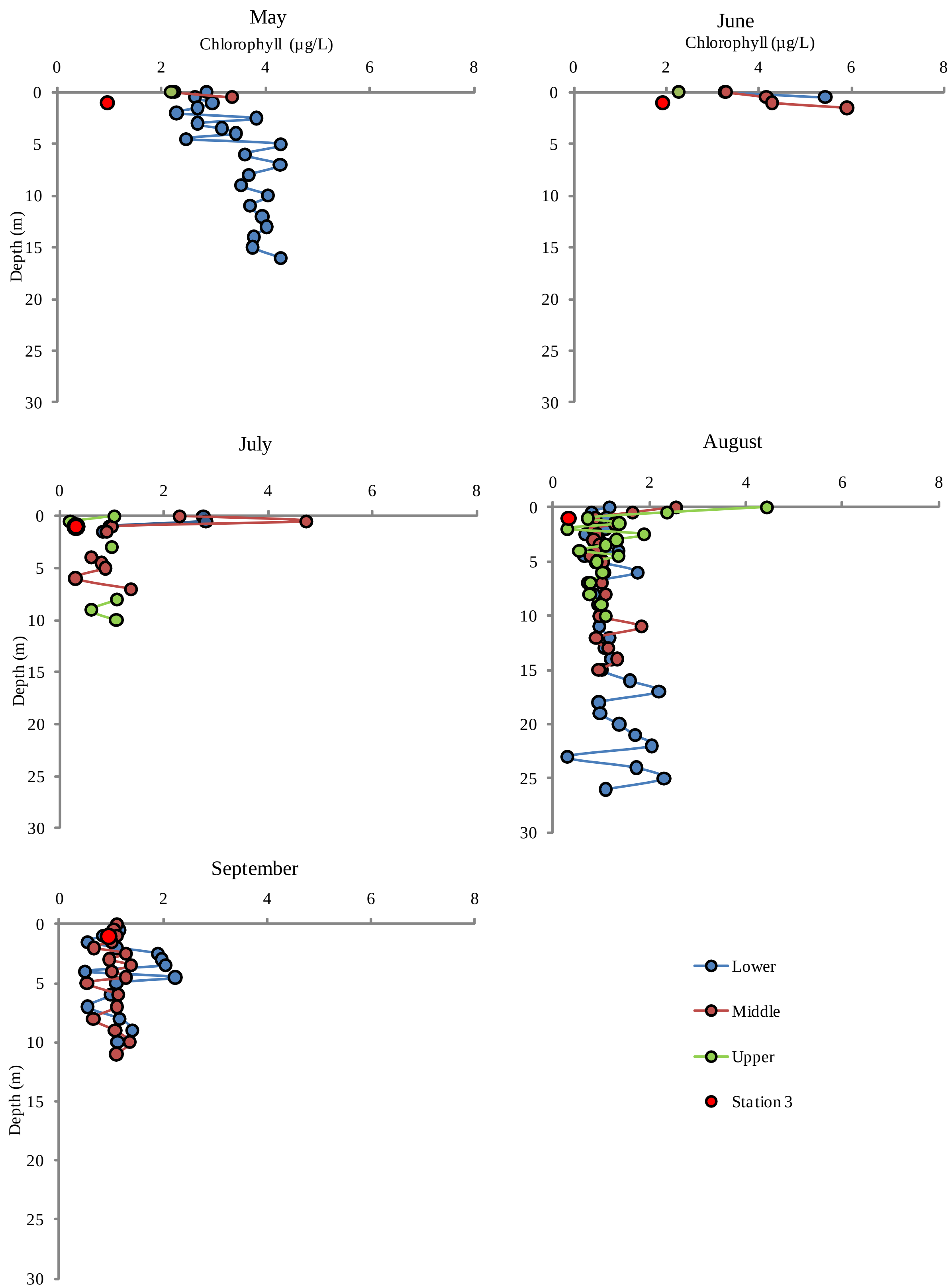



Figure 17.–Karluk Lake AUV chlorophyll depth profiles by region and month compared to traditionally collected data, 2009.

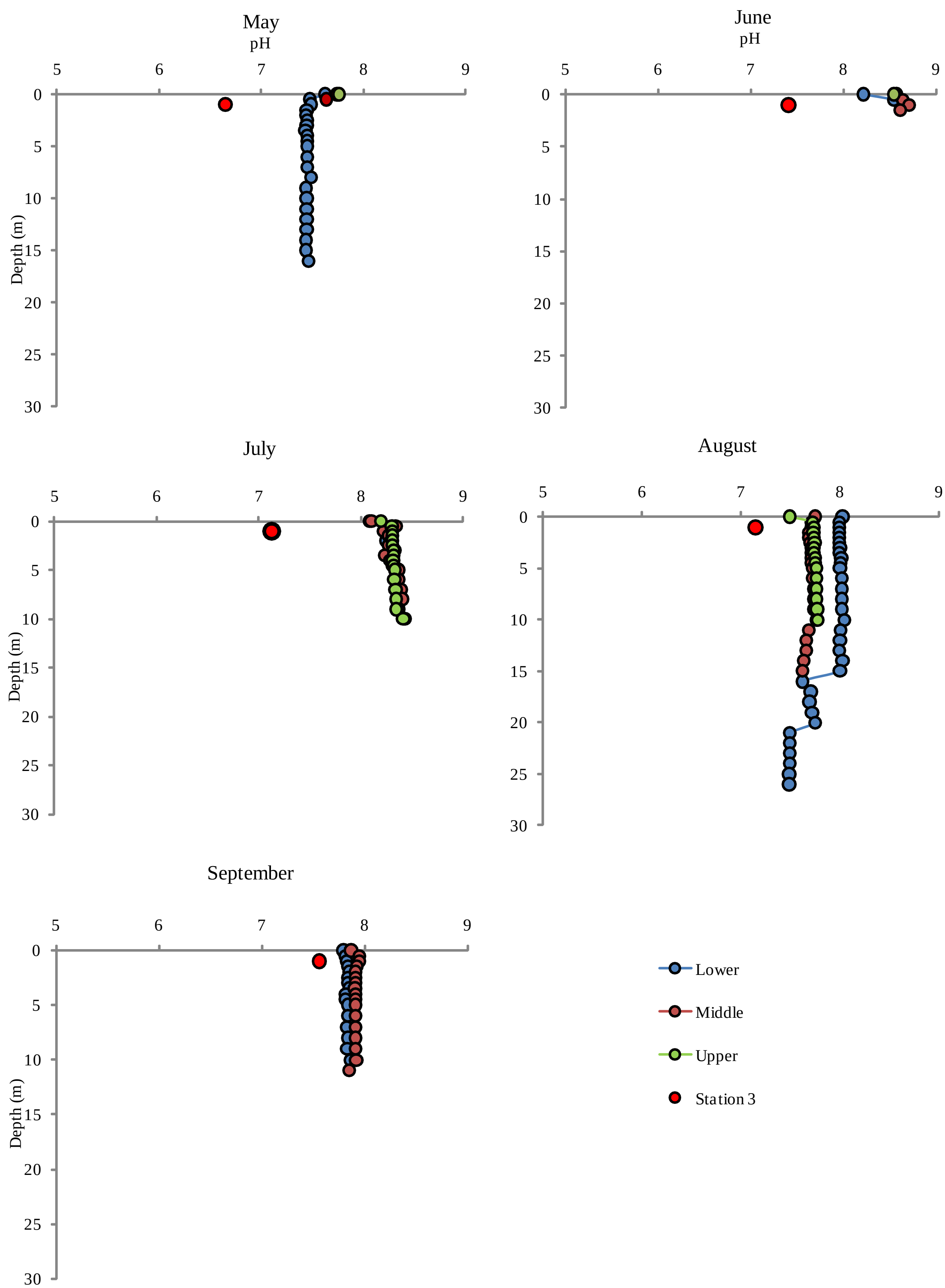



Figure 18.–Karluk Lake AUV pH depth profiles by region and month compared to traditionally collected data, 2009.

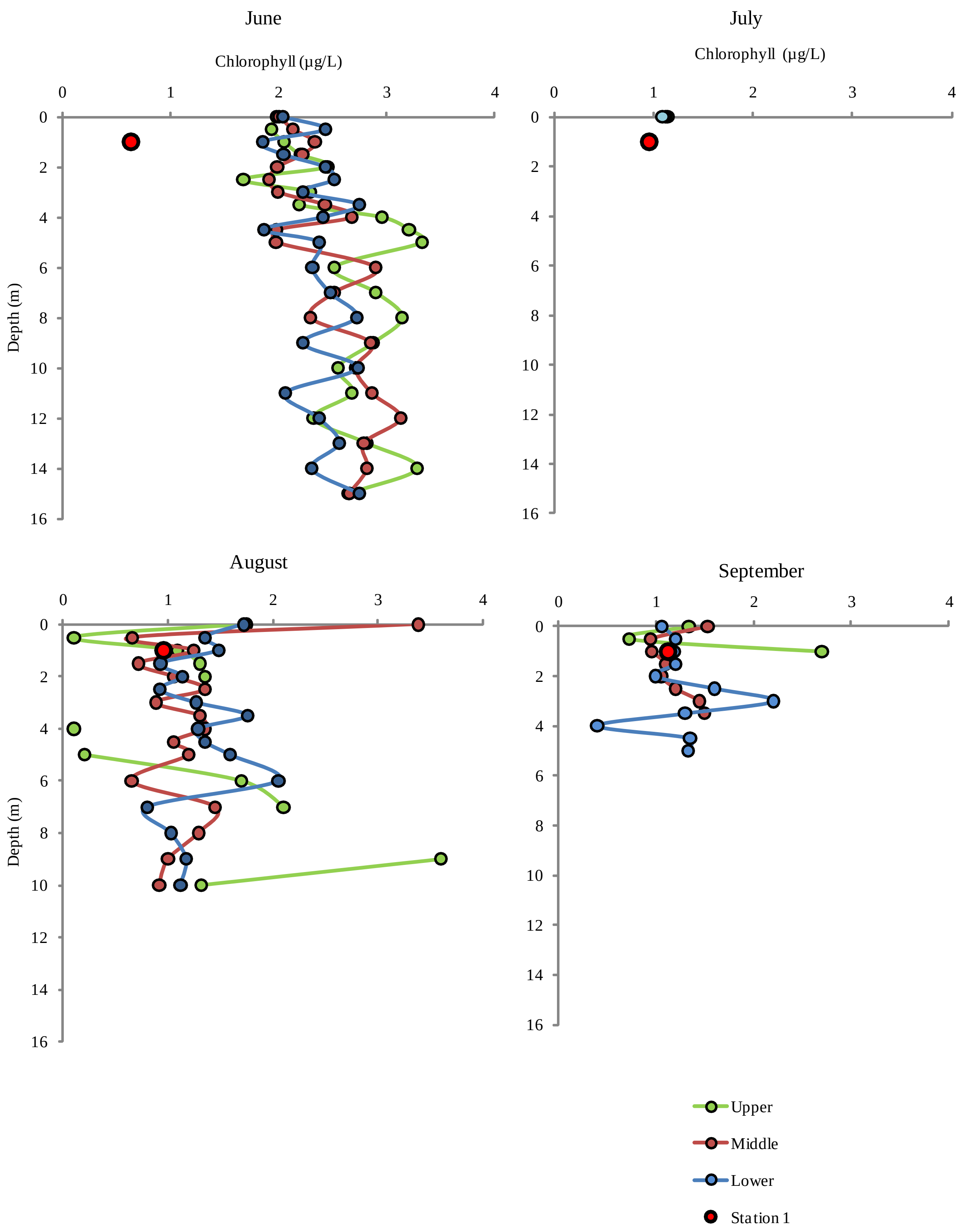



Figure 19.–Frazer Lake AUV chlorophyll depth profiles by region and month compared to traditionally collected data, 2009.

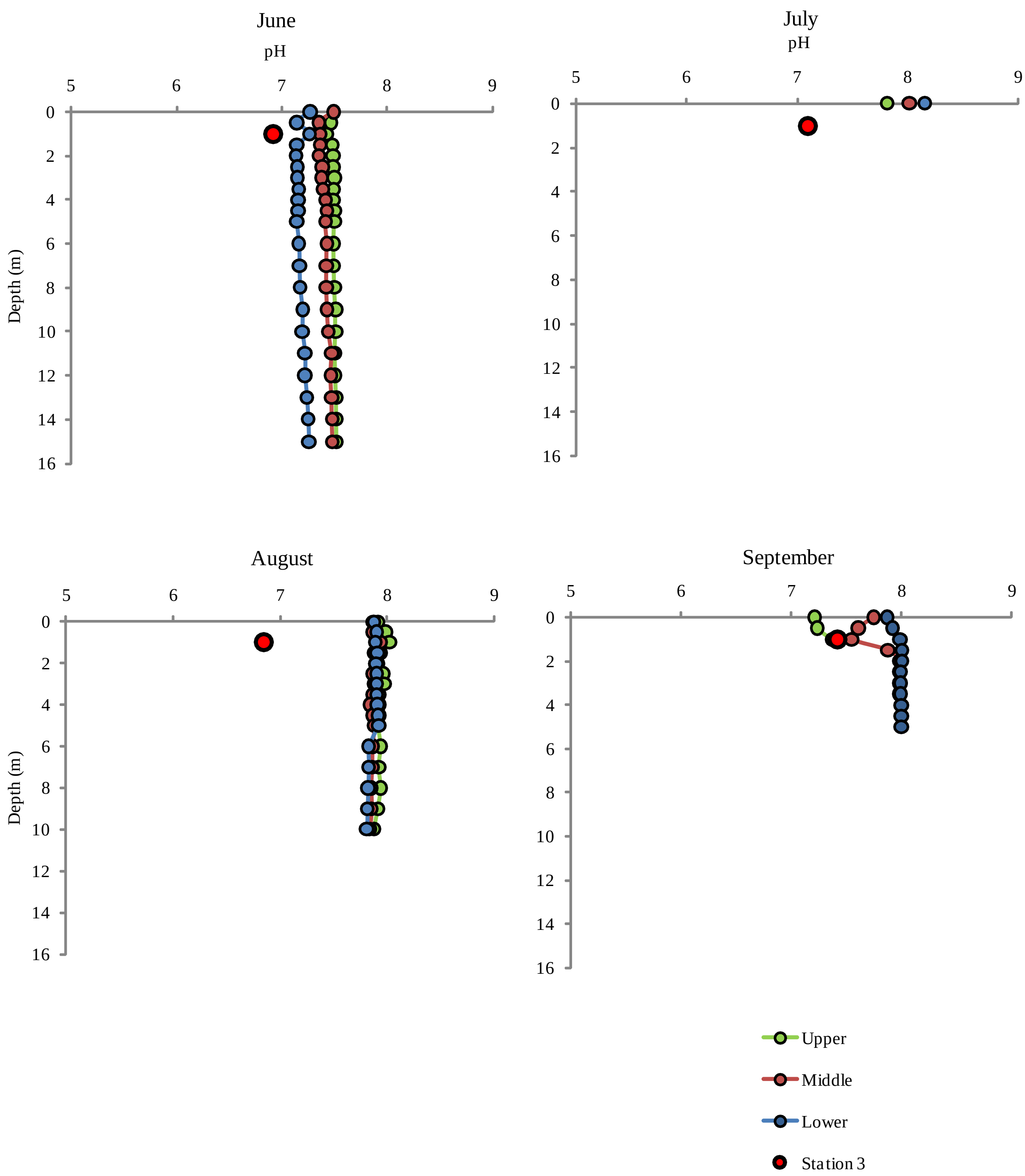



Figure 20.–Frazer Lake AUV pH depth profiles by region and month compared to traditionally collected data, 2009.

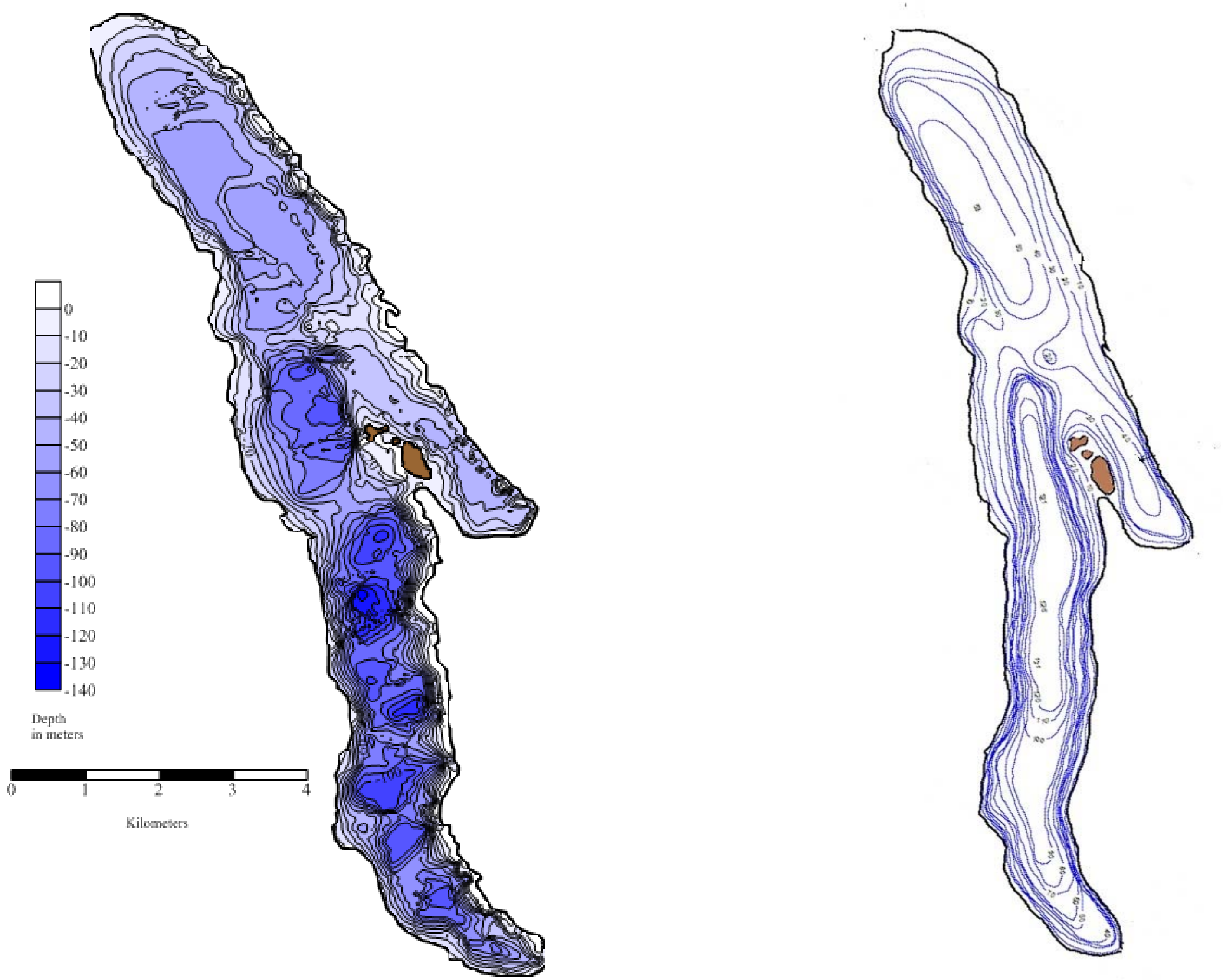



Figure 21.–Karluk Lake bathymetric maps comparing AUV-based (left) and original (right) maps.

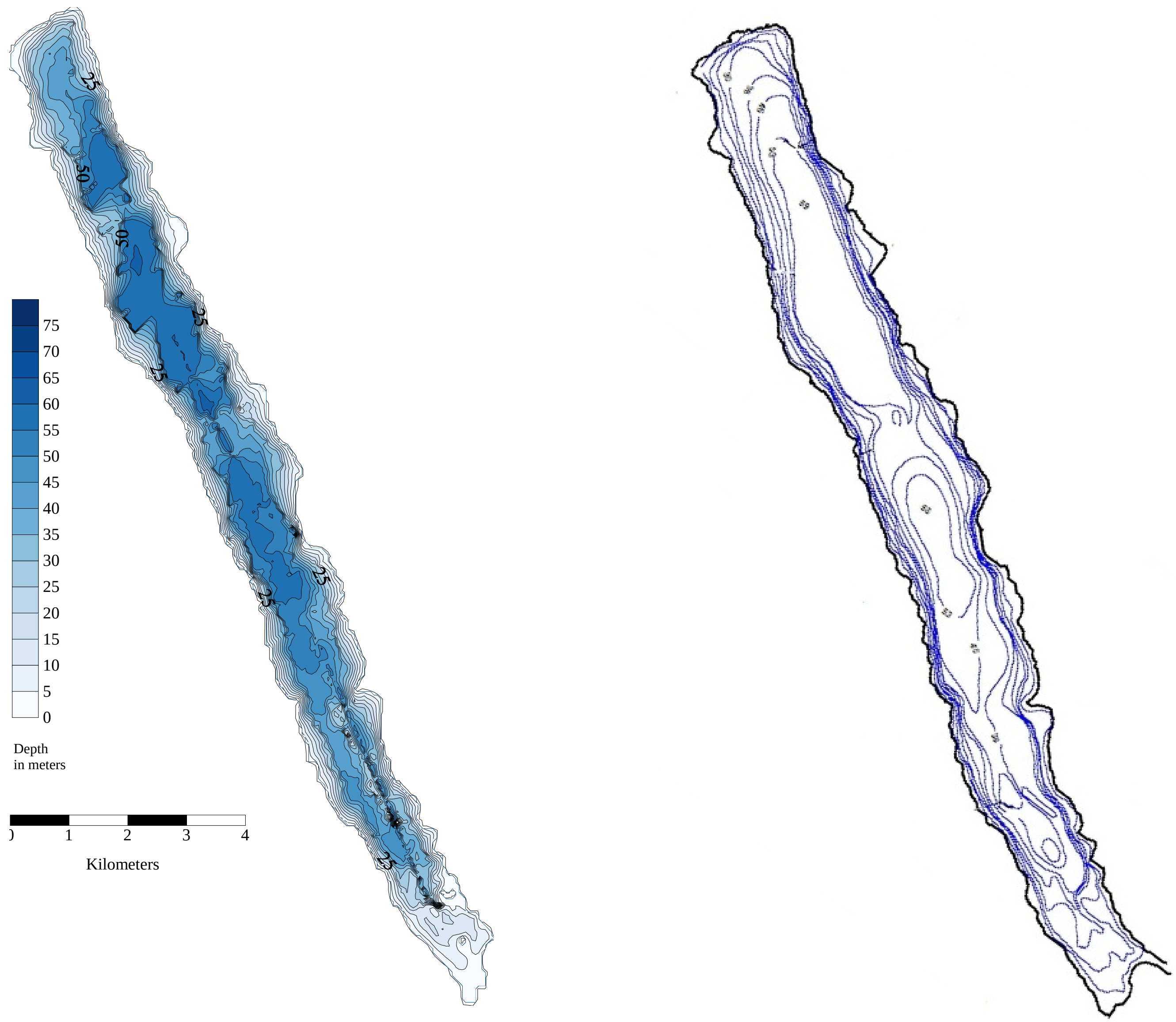



Figure 22.–Frazer Lake bathymetric maps comparing AUV-based (left) and original (right) maps.

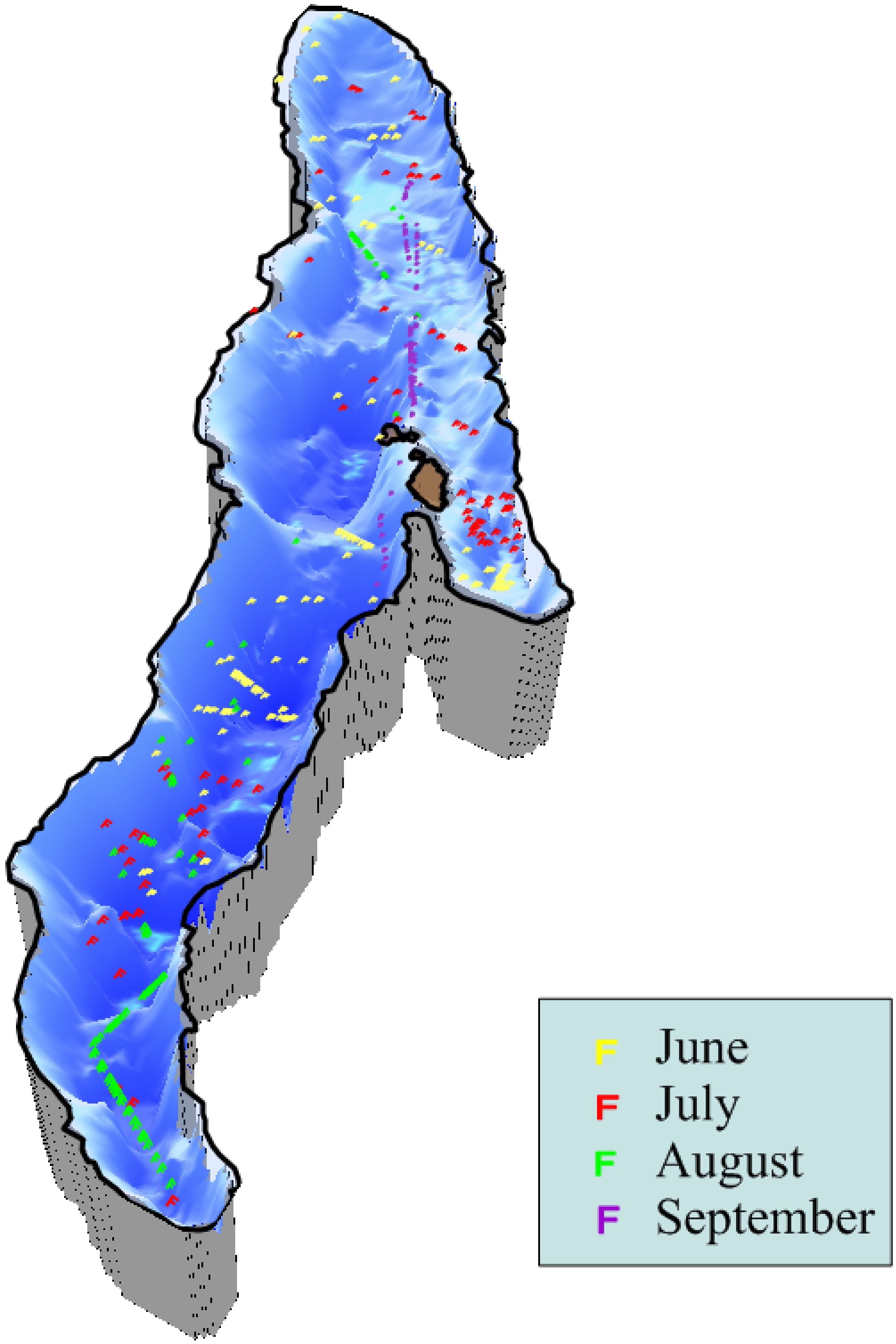



Figure 23.–Map of fish presence by month in Karluk Lake, 2009.

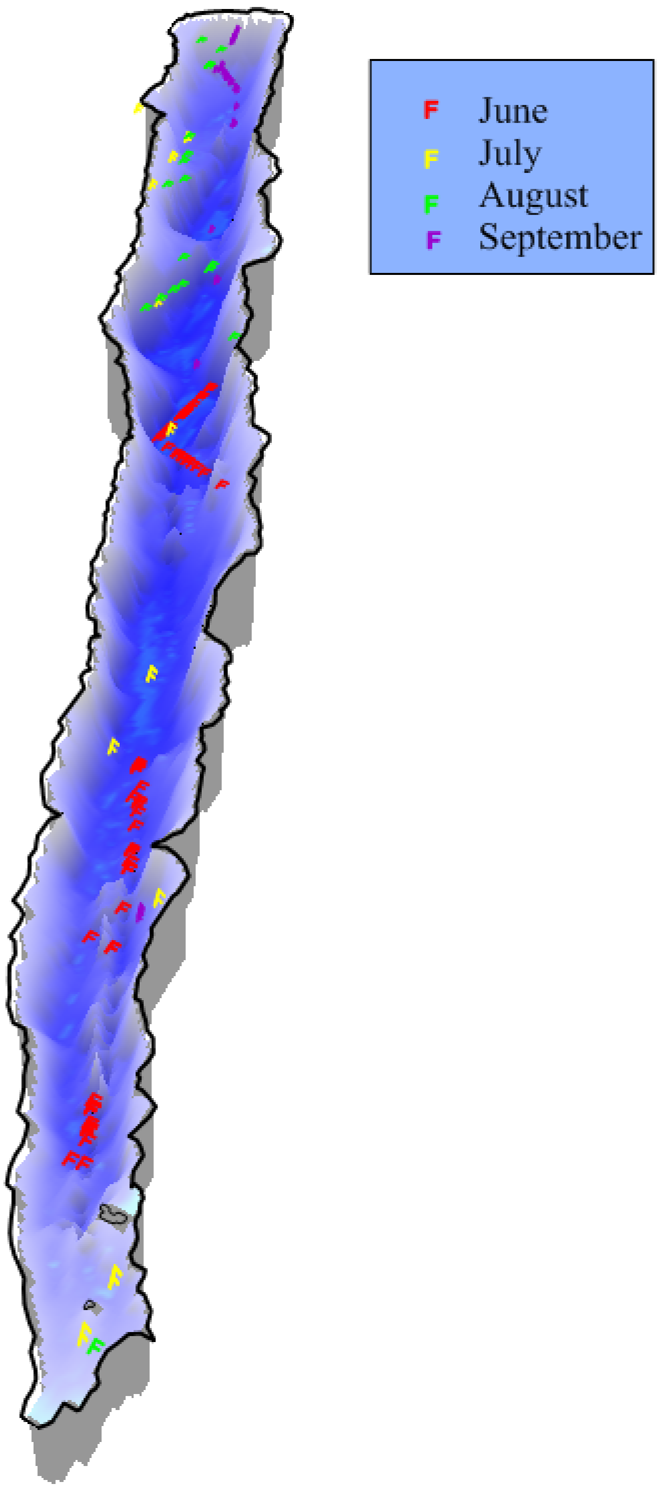



Figure 24.–Map of fish presence by month in Frazer Lake, 2009.

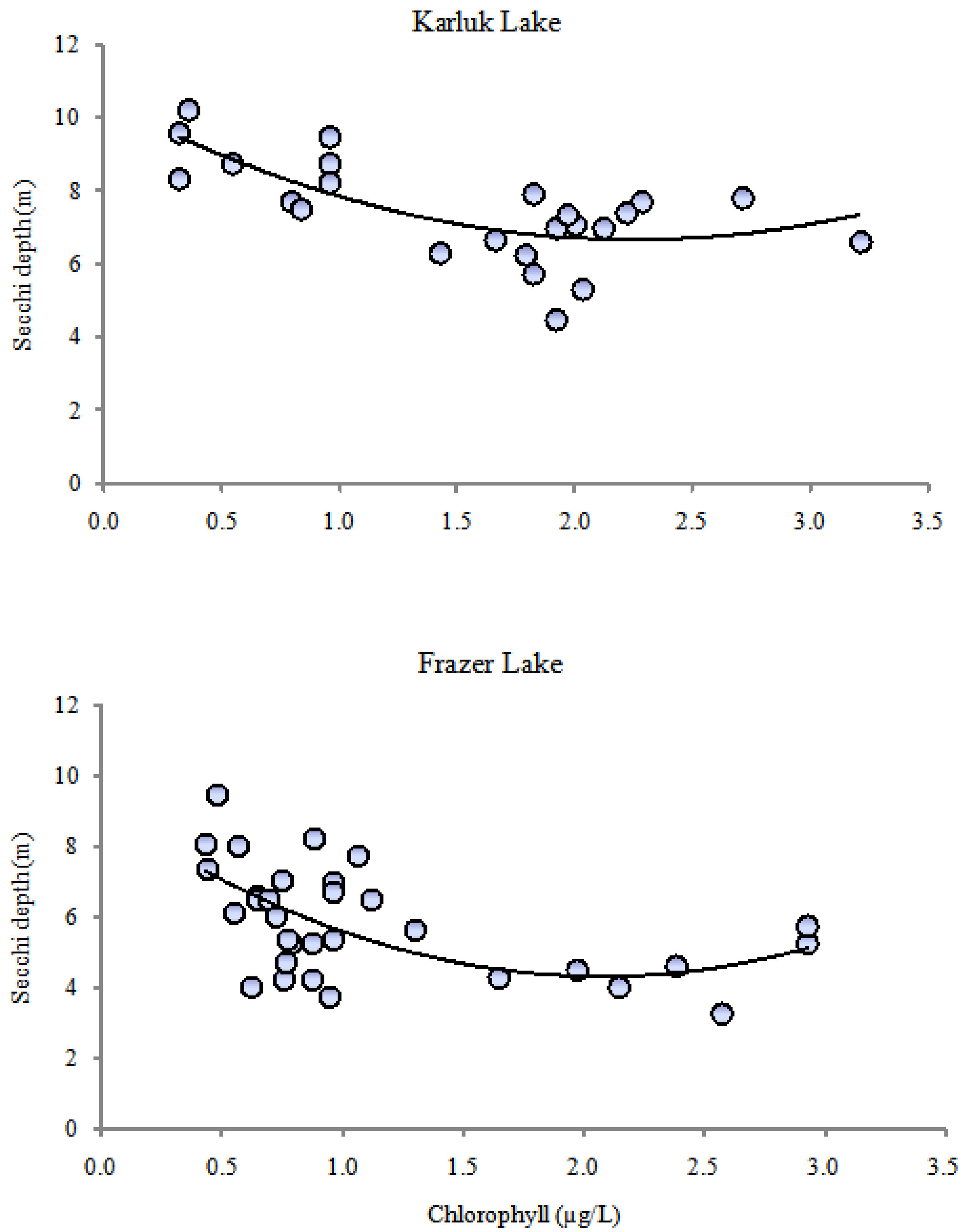
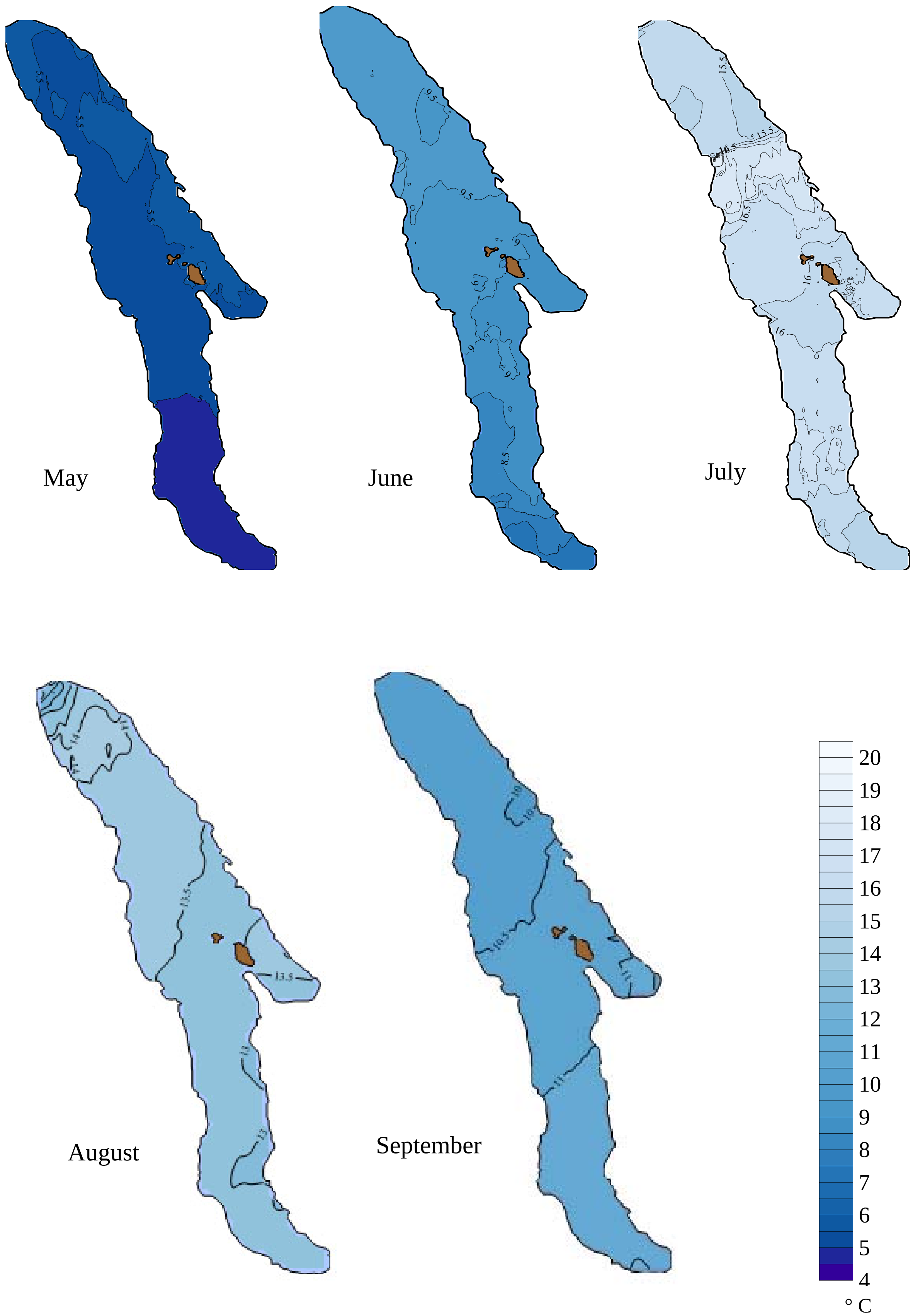


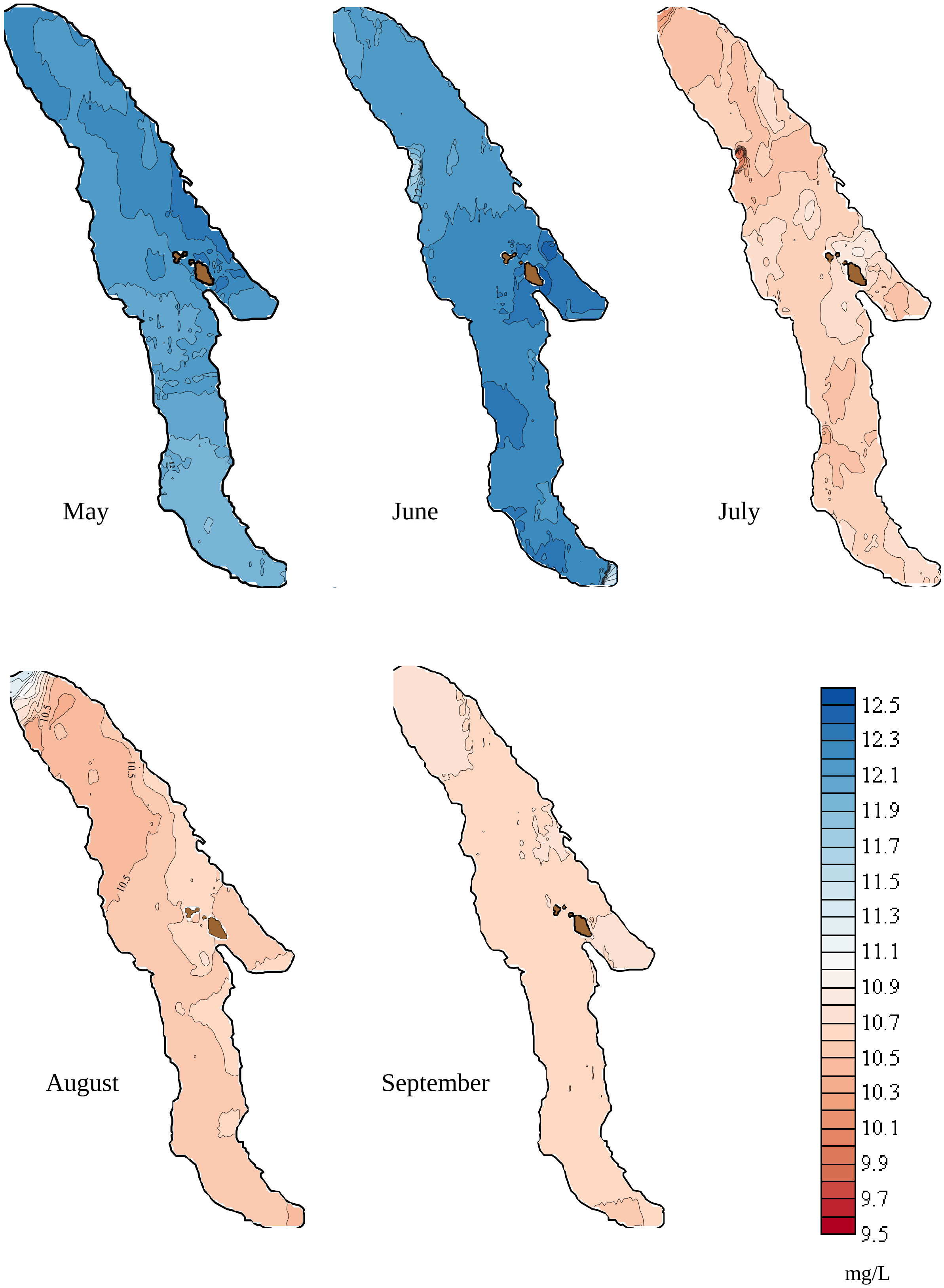

Figure 25.–Comparisons of chlorophyll-*a* concentrations to Secchi disc depths for Karluk and Frazer lakes, 2009.

# APPENDIX A: KARLUK LAKE WHOLE-LAKE SURFACE PHYSICAL DATA PROFILES.

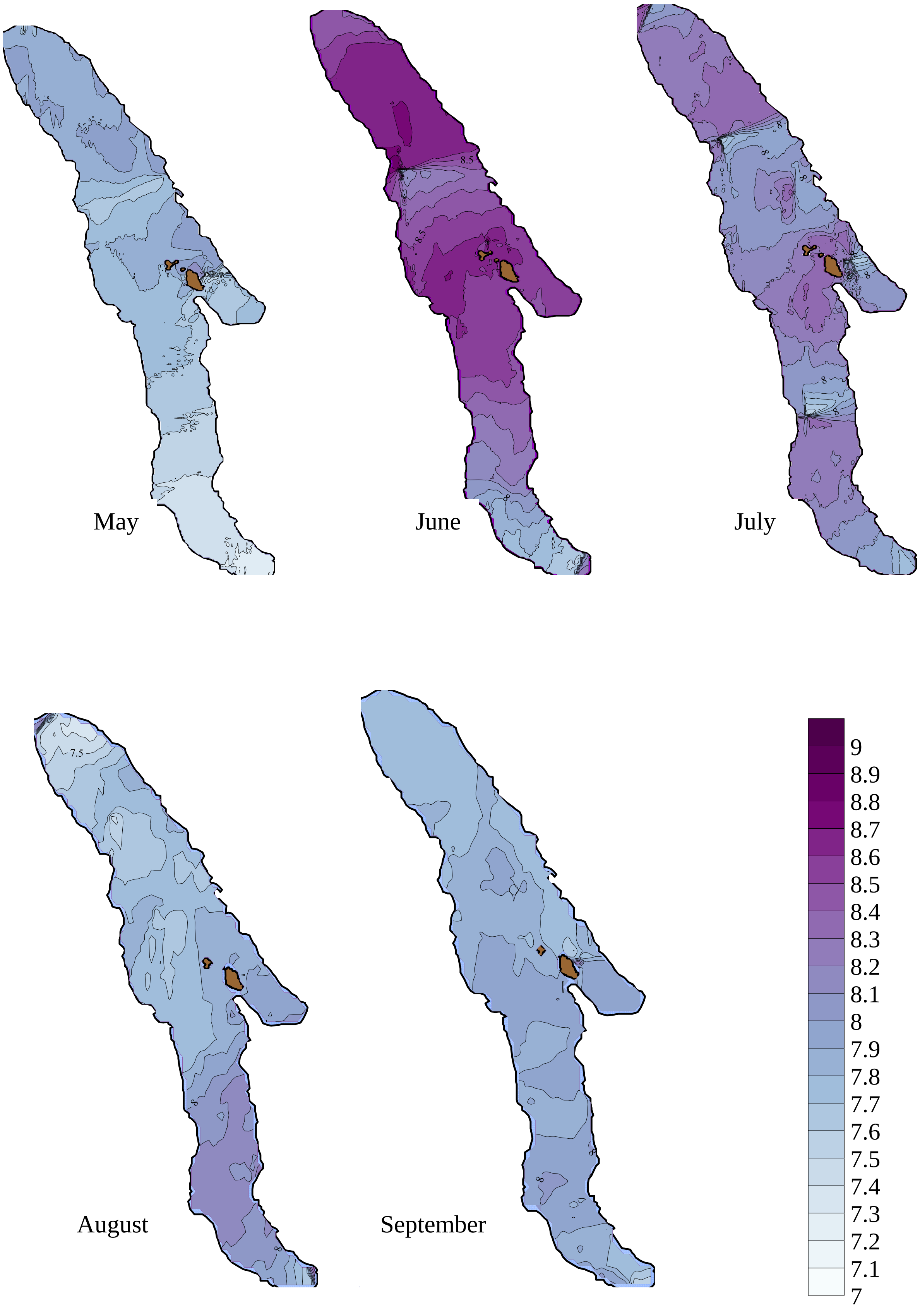
Appendix A1.–Karluk Lake surface temperatures (°C) by month, 2009.



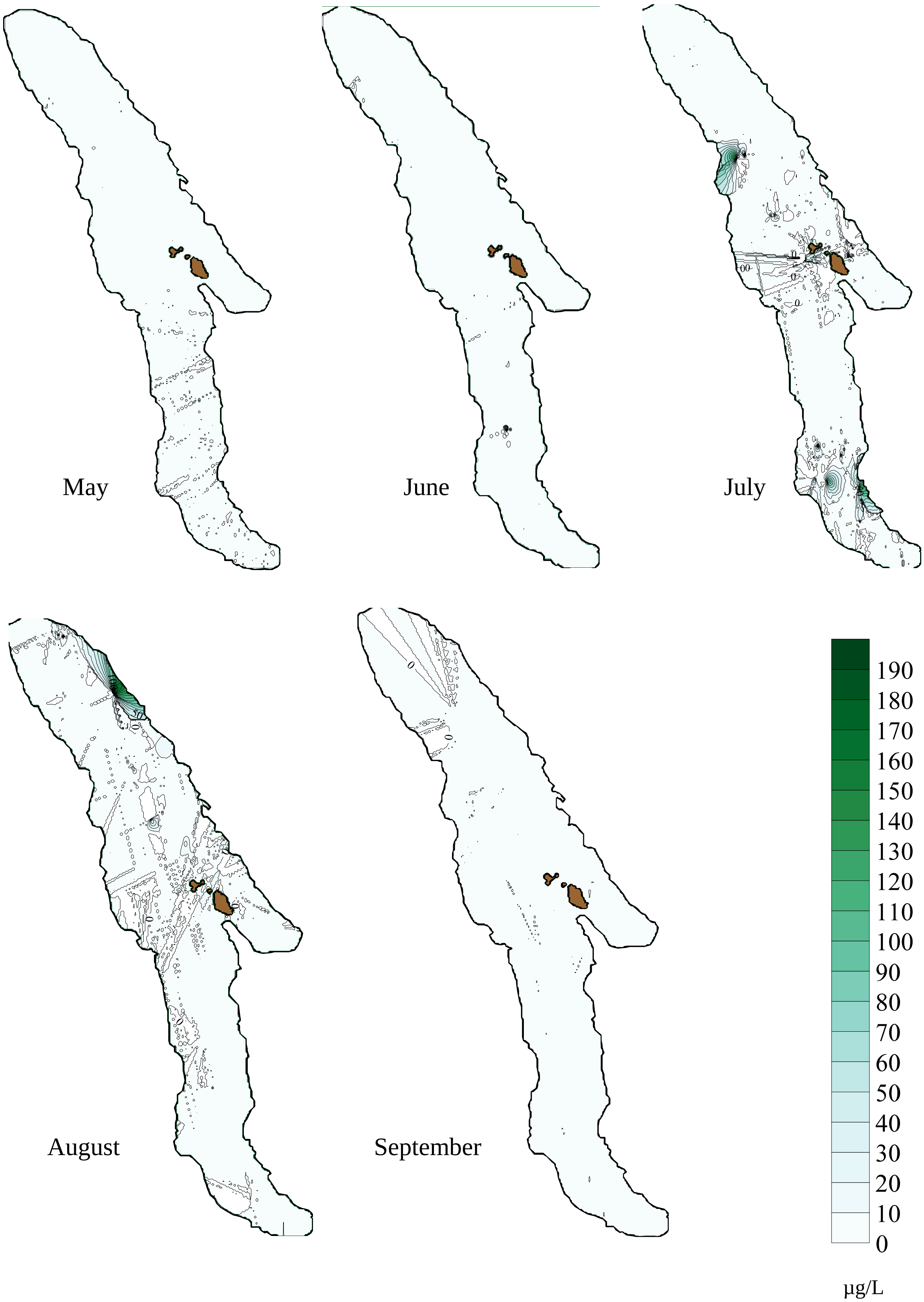
Appendix A2.–Karluk Lake surface dissolved oxygen concentrations (mg/L) by month, 2009.



Appendix A3.–Karluk Lake surface pH by month, 2009.

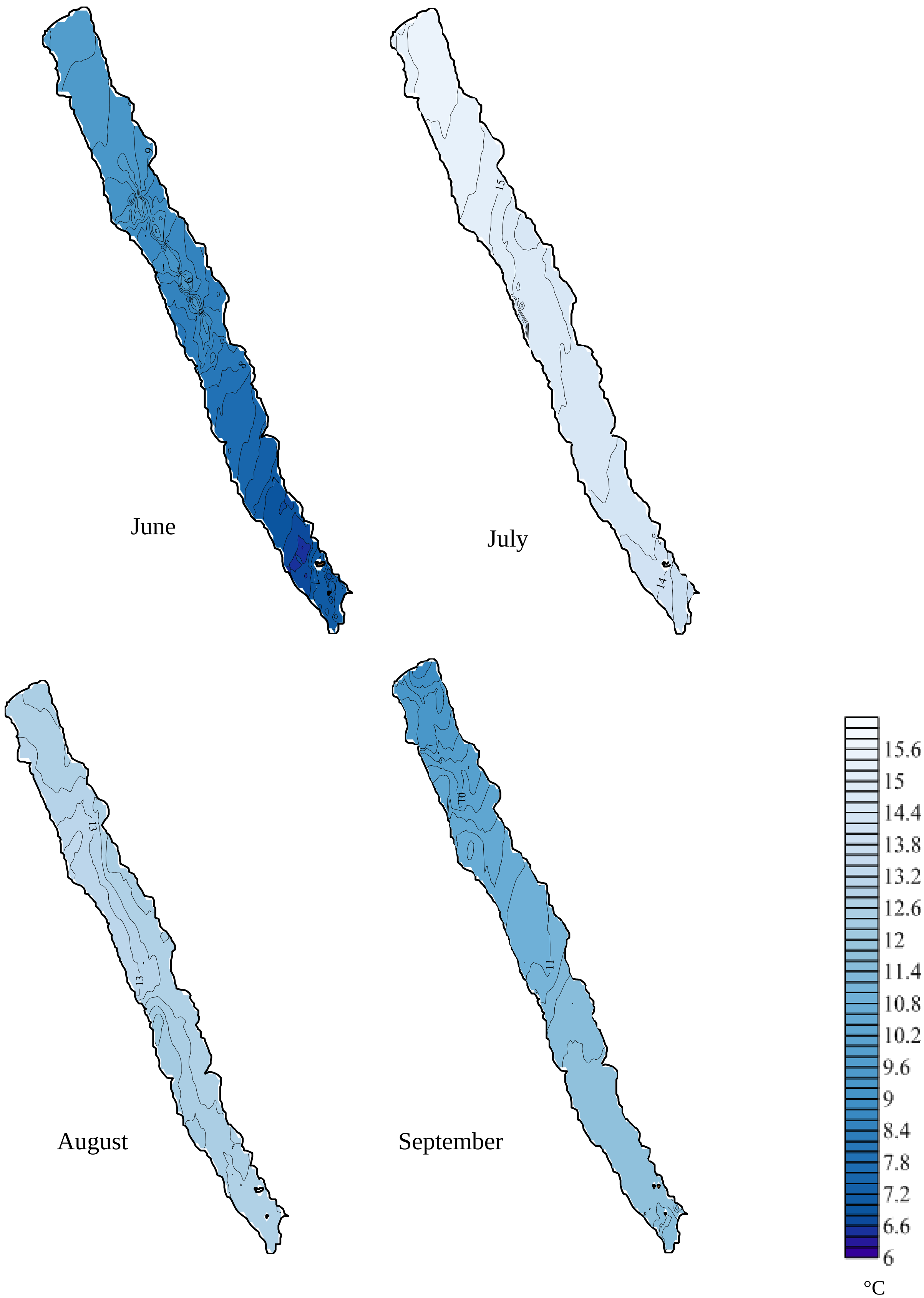


Appendix A4.–Karluk Lake surface chlorophyll concentrations (µg/L) by month, 2009.

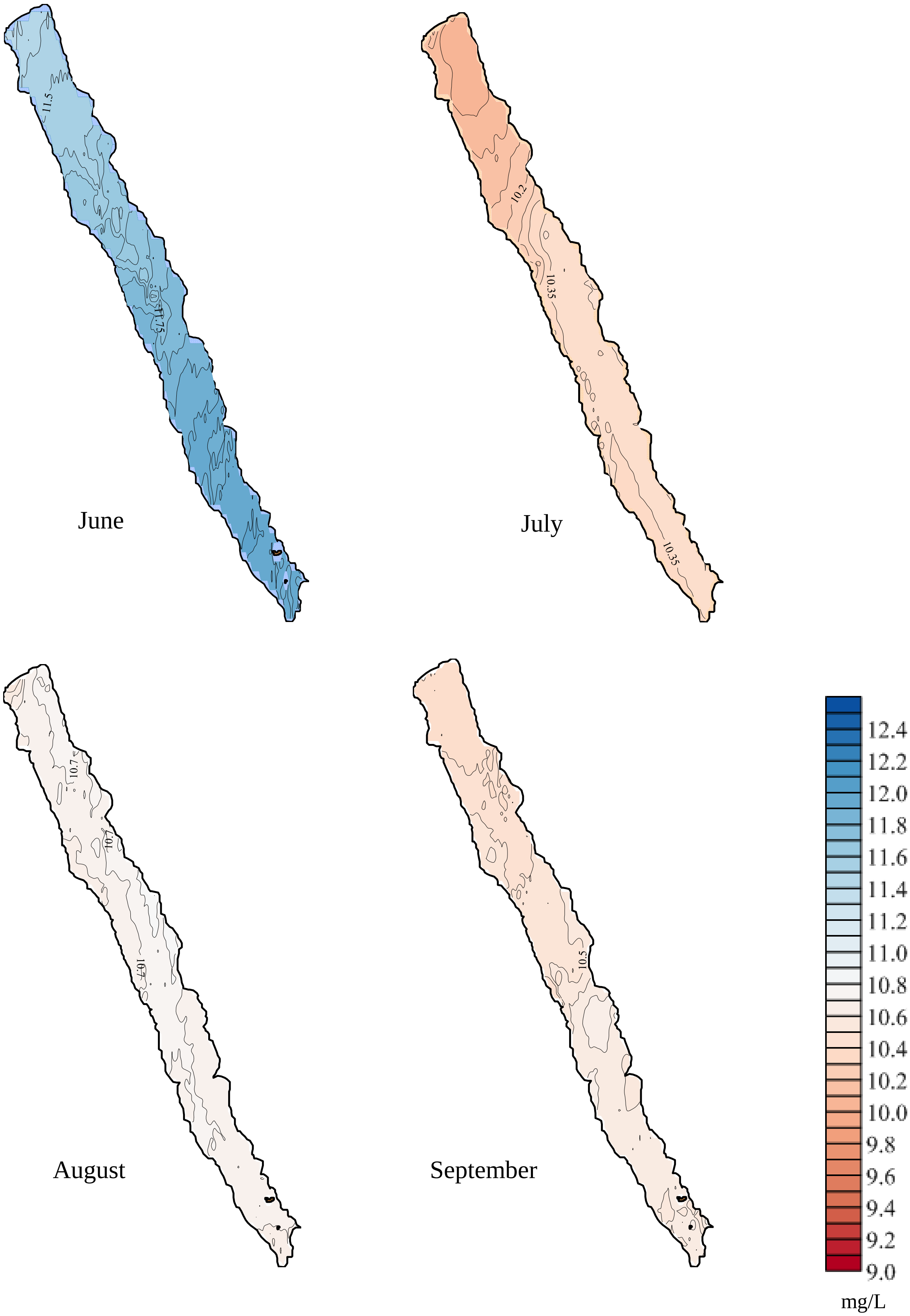


# APPENDIX B: FRAZER LAKE WHOLE-LAKE SURFACE PHYSICAL DATA PROFILES.

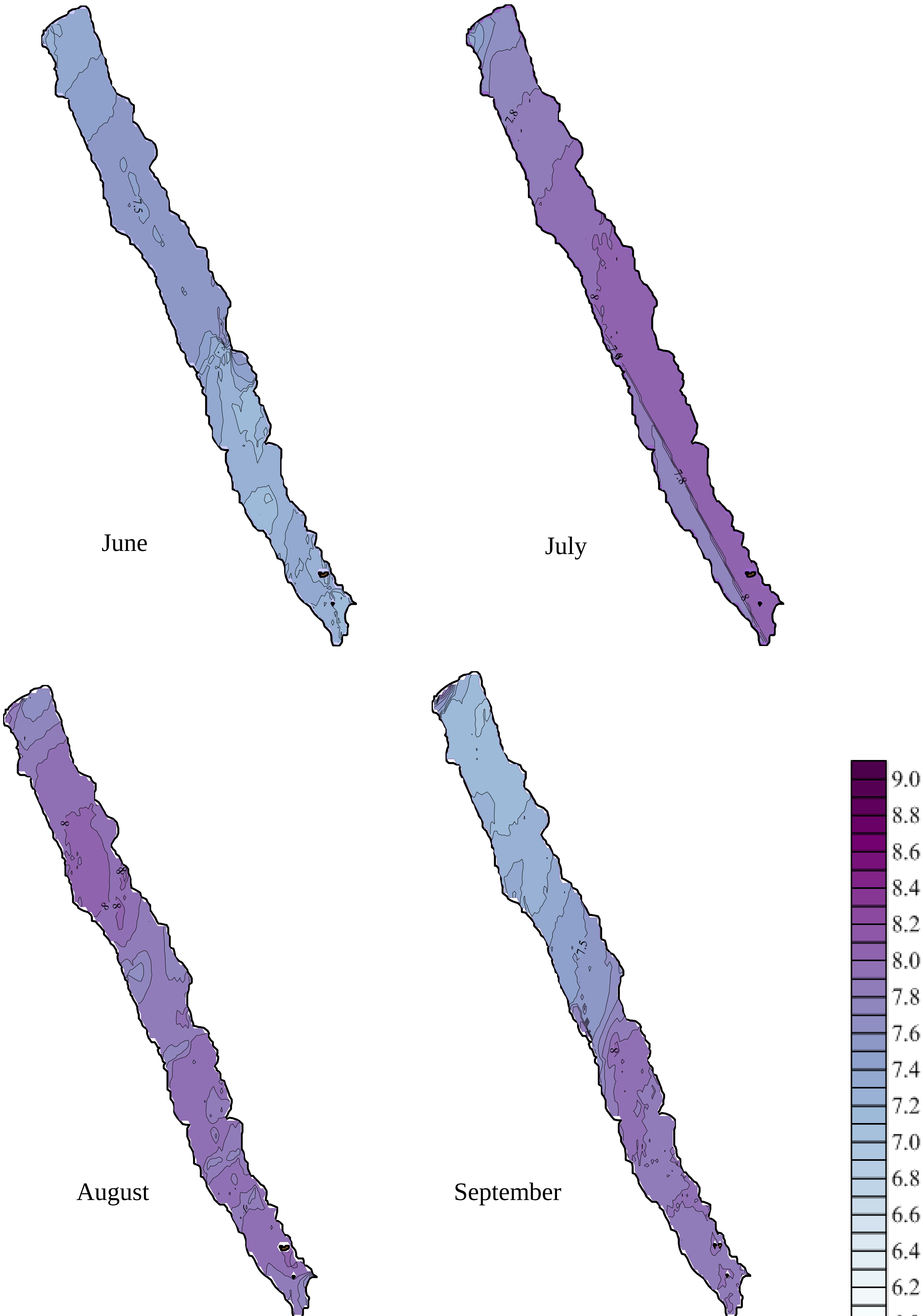
Appendix B1.–Frazer Lake surface temperatures (°C) by month, 2009.



Appendix B2.–Frazer Lake surface dissolved oxygen concentrations (mg/L) by month, 2009.



Appendix B3.–Frazer Lake surface pH by month, 2009.



Appendix B4.–Frazer Lake surface chlorophyll concentrations (µg/L) by month, 2009.